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13. ABSTRACT *(Maximum 200 Words)*
This project had the objective of developing computer software to extract information from 3D human body laser scan surface data that is useful for military uniform sizing. Beecher Research (BRC) worked with a consortium of five other organizations in this project for the Apparel Research Network (ARN).

BRC contributed to algorithm and source code development for computer program functions which measure Stature, Cross-Shoulder Length, Sleeve Length, Pant Inseam, and circumferences of the Neck, Chest, Waist, and Seat. To gather data for testing, BRC was involved in laser surface scanning of subjects at the US Army Natick (MA) RD&E Center, and the US Marine Corp Recruit Depot, San Diego.

BRC evaluated the results of successive versions of the computer program ARNscan using comparable traditional measurements of the subjects and computer graphics displays of the measurements generated by ARNscan. Except for Sleeve Length, ARNscan functions producing consistent results were developed.

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AUTOMATING INFORMATION EXTRACTION FROM 3D BODY SCAN DATA

Final Technical Report

Contract SPO100-D-95-1011
Delivery Order 0003

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PREFACE

This report documents the work of Beecher Research Company (BRC) as part of a consortium of contractors in the Defense Logistics Agency Apparel Research Network. The consortium project was coded DDFG-T2P5 ("T2P5"), titled "Automating Information Extraction from 3D Body Scans". Other contractors also working under this title, and reporting separately, were Anthrotech (Yellow Springs, OH), Clemson Apparel Research (Clemson, SC), Cyberware (Monterey, CA), HAAS Tailoring (Baltimore, MD), Ohio University (Athens, OH), and Southern Polytechnic State University (Marietta, GA, "SPSU"). Their work is referenced here, and their reports should be consulted for complete documentation of this effort. In addition, anthropologists at the U.S. Army Natick (MA) Research, Development, and Engineering Center ("Natick") contributed expertise and resources.

At the beginning of T2P5, BRC was the task coordinator among Partners, developing and monitoring the coordination plans, leading the T2P5 scanning project at Natick, and the initial planning with the US Marine Corp Recruit Depot in San Diego ("MCRD") for the Field Test there. BRC also developed algorithms for converting clothing body measurements into software functions, and wrote some of those functions for the program ARNscan. After accumulating scan data at Natick and MCRD, BRC was responsible for measuring the data using ARNscan, evaluating the results, and developing recommendations for improvement. BRC also worked with SPSU in their development and testing of size selection tables for MCRD dress uniforms.

This report was prepared by Dr. Robert M. Beecher and Ms. Mary E. Gross.

Acronyms And Abbreviations Used In This Report

ARN	Apparel Research Network
BRC	Beecher Research Company
MCRD	U. S. Marine Corp Recruit Depot, San Diego
OU	Ohio University
SPSU	Southern Polytechnic State University
Natick	U. S. Army Natick (MA) Research, Development, and Engineering Center
T2P5	ARN Design & Development Focus Group Task 2, Project 5 "Automating Information Extraction from 3D Body Scan Data". This is the umbrella title for the project worked on by Anthrotech, BRC, Clemson Apparel Research, Cyberware, HAAS Tailoring, OU, and SPSU.

EXECUTIVE SUMMARY

Introduction. The objective of this delivery order was to develop a computer program that could automatically, accurately, and consistently extract useful information from 3D whole body laser scans. The scan measurements would then be used in a computer program to issue apparel to military recruits in training. BRC had a unique place in Project T2P5 because of our previous experience and expertise in anthropometry, computer software development, statistical analysis, 3D human body modeling, and scientific testing. Working with a consortium of Apparel Research Network Partners, BRC helped developed algorithms and computer source code, organized testing and evaluation projects, and led the initial planning and organization for a field test of the scanner and software at the San Diego Marine Corp Recruit Depot. The project should be seen as an iterative process of (1) gathering apparel measurement information, (2) software development to extract the measurements, (3) testing and evaluation, and (4) recommendations for improvement.

Natick Validation Study. There was little data available to test the first version of the software extracting 3D body scan measurements. In the fall of 1997, Beecher Research Company helped organize and direct a project to record a significant number of subjects using the Cyberware WB4 Whole Body scanner at the U. S. Army Natick RD&E Center ("Natick"). The purpose was to provide a database for the testing of software being developed to extract body measurements from scan data, in anticipation of a field test at MCRD San Diego. No comparable database had been previously assembled. In three sessions during October, November, and December, 135 men and women were scanned in five positions and measured using traditional anthropometric and tailoring techniques. Using the first versions of the ARNscan software, measurements were extracted and compared with the Expert measurements. The results documented successes and problems in measuring a large, diverse population. The database was then used as a test bed for successive versions of ARNscan software.

San Diego Marine Corp Recruit Depot Field Test. With the announcement of the Virtual Prime Vendor project at the MCRD San Diego, the T2P5 group proposed a field test for the 3D body scanner and ARNscan software. Working with the staff at the base, a plan was developed to scan and measure recruits in parallel with the three clothing issuing points: on arrival, at first fit of the dress uniform, and at final fit just before graduation. The same recruits would be scanned and measured at each point so that longitudinal data could also be gathered. Dress uniform size issues and alterations would also be recorded in order to facilitate the development of size selection tables for ARNscan. The initial role of BRC was in developing the plan, and coordinating with the Marines among the other participating Partners: Anthrotech, Cyberware, and OU. After visits to MCRD to document the issue process in the fall of 1997, BRC and the other contractors scanned and measured recruits during three sessions in March, April, and June 1998. BRC worked in the scanning operation and in gathering and analyzing the uniform issue data.

Software Development, Testing, and Evaluation. The focus of this project was to develop software that could automatically extract measurement information from 3D whole body scans. Automation refers to being able to extract measurements without any landmarks on a scan subject and with no software user interaction. This has been achieved in ARNscan. BRC functioned as coordinator for this task up to the start of the MCRD field test. Throughout the project, BRC has

worked with the other T2P5 partners to develop algorithms, write and implement source code, and test and evaluate ARNscan software. The basic software platform is Cyberware's CyScan.

After much discussion, T2P5 settled on eight measurements as an "A" list necessary for apparel size selection. These were the focus of software development and the report here. Evaluations used measurements taken by Dr. Bruce Bradtmiller (Anthrotech) using traditional techniques (Expert) as comparisons. These measurements are a guide to the consistency of the ARNscan measurements. The evaluations cover the last three versions of ARNscan: ver. 7.3 released summer 1998, ver. 8.0 released November 1998, and ver. 9.0 released February 1999. While the measurements in the summary below are in inches, the main body of this report uses metric measurements because (1) the Cyberware scanner records all data in metrics, (2) in accord with standard anthropometric procedures all Expert measurements were recorded in metrics, and (3) metrics allowed for more precision in analysis and evaluation.

1. Stature (Height). Stature is used to size the USMC BDU, trousers, and coat. Measuring Stature in scan data was a matter of finding the highest point. The best performing software was in ARNscan 9.0. The mean difference from Expert was –1.1", although it was very consistent with a standard deviation from the mean (SD) of 0.5". Thus, accurate Stature could be computed by adding the mean to a scan measurement.
2. Neck Circumference. Neck Circumference is used to size the USMC shirt. BRC developed an algorithm to iteratively find the minimum circumference that proved successful in extracting the measurement. The mean difference from Expert in ARNscan 9.0 is 0.06", with a SD of 0.3".
3. Chest Circumference. Chest Circumference is used to size the USMC coat and shirt. BRC developed an algorithm to find the correct height at which to extract this measurement from the scan data. Measurement extraction problems have included (a) accurate location of the height, (b) finding all points in drawing the circumference, and (c) loss of data from the sides of the chest due to segmentation errors. Best performing software was the BRC function (Geo2) in ARNscan 7.3 (mean difference 0.1") and the ARNscan 9.0 function (mean difference 1.0"). Standard deviations are large because the first suffered from problems of type (b), while the second has errors of type (a) and (c).
4. Waist Circumference. Waist Circumference is used to size the USMC coat and trousers. Because there is no landmark or anatomical feature where the USMC waist is measured, BRC developed a regression equation based on other ARNscan measurements to predict accurately the measurement level. The mean difference from Expert in ARNscan 9.0 is 0.4" with a SD of 0.6". Differences from Expert seemed to be the result mostly of waist fat that increased ARNscan measurements.
5. Seat Circumference. Seat Circumference is used to size the USMC trousers and coat. The software developed for this measurement has been very reliable. The best performing version was in ARNscan 8.0 with a mean difference of 0.2" and a SD of 0.3". Ver. 8.0 was closer to the expert value 94% of the time.
6. Cross Shoulder. Cross Shoulder is used to size the USMC coat and shirt. This has been a difficult measurement to extract because it is measured along the surface between shoulder edges that have no consistent landmark. Also, for size selection, this measurement needs to be very accurate. BRC developed part of the algorithm for this measurement. The evaluations of the measurement results were with an Expert surface measurement between the acromion landmarks – different from what Cross Shoulder attempts to measure. The mean difference in ARNscan 9.0

is 0.6" with a SD of 0.7". Improving the results will probably require developing a good error-detection tool.

7. Sleeve Length. Sleeve Length is used to size the USMC shirt. This is the most complex measurement to be extracted by ARNscan. It is composed of one-half Cross Shoulder plus the straight-line distance from the shoulder endpoint to the sleeve endpoint. Apart from the difficulties noted with the Cross Shoulder, the arm component of Sleeve Length has two problems degrading performance. First, drawing a straight line from the shoulder to the hand often passes through part of the upper arm, which does not emulate the path a tape would take. Second, automatically finding a point on the hand or wrist from which to offset a sleeve endpoint has proved most difficult of all ARNscan functions. ARNscan 9.0 has a new function to locate the thumb which appears to be consistent enough on which to base useful measurements. The mean difference is –0.1" and the SD is 0.6". An error-checking function to detect errors in hand location may also improve results.

8. Pant Inseam. Inseam is used to size the USMC trousers. This measurement is the height at which the body segmentation tool separates the legs from the torso. ARNscan 9.0 has a mean difference of –0.2" and a SD of 0.4".

Size Selection. BRC hired Carol Ring of SPSU as a consultant from December 1997 through May 1998 to develop size selection tables for the USMC dress uniform. During and after this period, BRC supported her work by providing ARNscan measurement results, evaluating sizing problems in terms of the measurement functions, developing new measurement tools to test size selections, and doing size selection for additional scans to increase Ring's sample size.

1.0 Introduction

1.1 Background

In the proposal for membership in the Apparel Research Network (ARN), Beecher Research Company proposed to develop software which would extract measurements from high resolution 3D laser surface scans recorded by devices such as the Cyberware WB4 whole body scanner. At the time, BRC had twelve years experience in analyzing 3D human body data. In 1996, BRC wrote a successful proposal for an ARN Short Term Project based on the original, entitled "Automating Extraction Of Useful Information From 3D Body Scan Data", coded DDFG-T2P5 among ARN projects. Clemson Apparel Research also submitted a successful proposal under this title. The significance of the project was to bring increased automation and accuracy to the problem of size selection of military apparel. At this point, the project objective was to measure 3D scans, but was not tied to any particular application. In the fall of 1996, ARN Program Management opened up T2P5 to other ARN Contractor/Partners, and the project became a consortium of Anthrotech, Cyberware, HAAS Tailoring, and Ohio University.

1.2 Objective

After the formation of the consortium, the objective became to thoroughly study the fit requirements of military dress uniforms, and to translate those requirements into a highly automated, user-friendly computer program that could quickly specify and issue the correct sizes of military apparel. BRC was the initial project coordinator, and our objective was to lead in developing roles for the consortium members as part of an overall development plan, and to facilitate communication among the Partners and with the Program Manager. In June 1997, this objective was narrowed to focus on the possible installation of an automated measurement and sizing system at the U.S. Marine Corp Recruit Depot at San Diego. Apart from this administrative role, BRC has had the technical objective of finding the best algorithms to translate needed body measurements into computer software, and to test and evaluate the results in light of the constraints of operating with the available 3D scan data.

1.3 Scope

The principal tasks were (1) software development, (2) database development and testing, and (3) size selection support.

The approach of BRC (along with other Partners) to software development was (1) understand the definition of body measurements relevant to apparel sizing, (2) translate the definitions into practical algorithms for software development, (4) participate in writing the computer program code, (5) test software versions using the available database, and (6) recommend improvements in the software. This was an iterative process throughout the course of this delivery order.

In database development, BRC worked with the other Partners to design protocols for operations at Natick and MCRD San Diego which would yield the greatest amount of the most useful and "cleanest" data for testing the software. We also approached this task as a test for the rapid and consistent processing of subjects for future installations.

The lead in size selection development has been Carol Ring at SPSU. BRC has operated as a service adjunct to Ring in order to supplement her capabilities and resources in applying tables to scan

measurement data. BRC also supported Ring by interpreting the functioning of ARNscan with respect to particular subject measurements.

2. Technical Approach

2.1 Software Development, Testing, and Evaluation

2.1.1 Introduction
The primary task in this delivery order was to develop computer software that could input data recorded by the Cyberware WB4 Whole Body Scanner, and compute body measurements useful for military apparel size selection. BRC brought to the task previously developed software (*ShapeAnalysis*) for high resolution body surface data, which could perform some of the basic operations required for the program which became known as ARNscan. With the inclusion of ARN Partners Cyberware, Ohio University, Clemson Apparel Research, Anthrotech, HAAS Tailoring Co., and Southern Polytechnic State University in this task, BRC worked to incorporate its software functions into ARNscan. ARNscan is a derivative of Cyberware's CyScan software that controls the WB4 and performs basic graphic displays. It is written in c++ and Tcl/Tk. It was agreed that this would be the software "platform" onto which software functions developed by T2P5 Partners would be installed by Cyberware. At the beginning there was little data for testing, no experience in using this data and it was agreed that Partners could work in parallel to develop functions for ARNscan (such as one to measure chest circumference). The functions would then be tested and the best performing software would be incorporated into ARNscan.

After the first release of ARNscan from Cyberware, BRC worked to understand its organization and port code developed for scan measurements into it. Measurement functions developed by BRC and other Partners were tested and evaluated by us on the available scan data. Algorithms for the measurement functions were developed by "translating" Expert traditional tape measurements into a process that could be converted into computer software. The list of measurements to be pursued were decided upon by the ARN Partners whose expertise was in apparel – HAAS, Clemson Apparel Research, and Southern Polytechnic State University (SPSU). Thus, an "A" List of essential measurements was agreed upon:
(1)   Stature (Height)
(2)   Neck Circumference
(3)   Chest Circumference
(4)   Waist Circumference
(5)   Seat (Hip) Circumference
(6)   Cross Shoulder
(7)   Sleeve Length
(8)   Pant Inseam (Crotch Height)

Other measurements, such as Overarm Circumference, were also desirable as they are used in tailoring made-to-order clothing. These additional measurements would require more than one scanning pose, however. During the Natick Validation Study, different poses were used in part because there was no application goal that necessitated limiting the time to scan a subject. With the adoption of a goal to issue dress uniforms to recruits at the Marine Corp Recruit Depot (MCRD) in San Diego, it was realized that the time involved in more than one scan was unacceptable if a large number of recruits were to be processed quickly. Thus, a commitment was made to extract only those measurements available from one scan pose. Fortunately, SPSU's study of sizing and fitting requirements for the USMC dress uniform found that the "A" List was sufficient.

The performance goal for ARNscan was to develop software that was

(1) Accurate – The measurement values were compared with comparable measurements made on the same subjects by an Expert measurer using traditional tape or calipers. The goal was to emulate, to the extent reasonable, the traditional measurement.

(2) Consistent – We recognized that measuring 3D data points representing a body surface was not the same as measuring a living body itself. With that in mind, it was a goal of software development that the measurement functions perform in a consistent manner on the data, performing mathematically in a predictable way.

(3) Robust – When the project began, there was little whole body scan data on which to test the software. Even a year later, there were perhaps only about 35 scans with accompanying Expert measurements. It was realized that the software functions could be easily "tuned" to these few scans. That is, we could customize the software to extract measurements very accurately off of those scans, but the functions may not perform well on a larger variety of human body size and shape. This led to the Natick Validation Study that was used to test the robusticity of the software. The goal was to have software that could accurately measure any subject that might be encountered.

(4) Simple to use – ARNscan can only be useful in a work area not staffed by computer experts. It was determined that ARNscan operation should require minimal expertise.

(5) Automatic - This last goal meant that the ARNscan software must ultimately require little or no user interaction in computing body measurements. Further, the subjects were to have minimum preparation before scanning, such as body markings for measurements identifiable on the scans or the poses during scanning. It was realized, however, that these goals were to be reached only through an iterative process of (a) algorithm development, (b) software implementation, (c) testing, and (d) evaluation.

BRC has had a role in all aspects of these iterations. This section discusses software functions that have evolved for each measurement being used for apparel size selection, and the role of BRC. The discussion of software will begin with version 7.3 of ARNscan. This version incorporated what was learned from the Natick Validation Study, and was then applied to measuring the scans recorded at the MCRD in the spring of 1998. See Section 2.2 for a description of the Natick and MCRD data recording tasks. All of the measurement data discussed below, ARNscan and Expert (called "Traditional" in the file) are contained in the Microsoft Excel file **ARNscanMCRDmeasurements.xls** at BRC.

Expert measurements used for comparison in these discussions are those taken by Dr. Bruce Bradtmiller (Anthrotech) on the subjects during the scanning sessions.

2.1.2 Analysis of Measurement Functions

The software functions developed to measure the whole body scan data are discussed individually. Each measurement presented different challenges in emulating a measurement taken on a living person, and the history of the software developed for each function followed a different path. Beginning with ARNscan7.3, the software was used to extract measurements from the scans recorded at the Marine Corp Recruit Depot (MCRD) in San Diego in 1998. ARNscan 7.3 and 9.0 were used to measure all scans from all three scanning sessions. However, due to a time constraint, ARNscan8.0 was used only to measure subjects being issued and first fit with their dress uniforms (T19). Thus,

the analyses presented here are mostly based on measurements from the T19 sample. There were a total of 202 recruits scanned at T19-20, but only those recorded on 14 April (n=70) were measured using ARNscan8.0 for some measurement functions.

All measurements were recorded and analyzed in millimeters. Statistics were computed using SPSS and Microsoft Excel.

Along with the measurement values, the software functions were evaluated graphically. For each scan measured in ARNscan, the results were displayed on the screen by having a line follow the path of the measurement. Comments were recorded concerning any problems related to scan quality or software performance vis-à-vis expectations. These comments were used in evaluations of the software to help explain differences in performance of two different software functions or the software measurement when compared with the Expert. All comments are in **ARNscanMCRDmeasurements.xls.**

While gross evaluations have been made using the Expert values as a standard, it was observed that in several cases the software function was performing consistently and as expected, even though the results compared with the Expert values didn't reflect that. Thus, the Expert values should be seen more as a check on the software performance, calling attention to results deviating noticeably from the expected ("outliers"). The evaluations below represent the combined assessment of comparison with Expert values, observations of graphic results, and performance expectations of the software developers. Although evaluations represent judgments concerning the quality of the results, it was not the responsibility of this project to provide acceptance criteria for the measurement functions. These criteria will come from a work-sampling study performed at MCRD San Diego after the conclusion of the BRC project.

Charts and Statistics. The Charts accompanying each measurement discussion all have the same format. The Charts graph the frequency distribution for the differences between ARNscan measurements and Expert measurements for the scans that were analyzed. Thus, a negative value means that the ARNscan value was smaller than the Expert, while a positive value means that the ARNscan value is larger than the Expert. The X-axis contains the range of values for ARNscan minus Expert, while the Y-axis has the percentage of subject scans for each difference value. Within each measurement discussion, the scales are the same, also, in order to facilitate comparisons of the different ARNscan measurement tools. The summary statistics for the data in each Chart are contained in the upper right corner of that chart. The number of scans analyzed ("n") for each Chart differs because of two factors: First, for some functions, there were failures or software crashes which prevented getting any meaningful measurement. Second, as noted above only a limited number of scans were measured in evaluating ARNscan8.0. For some comparisons, n was reduced in other versions to compare with 8.0. This report uses metric measurements because (1) the Cyberware scanner records all data in metrics, (2) in accord with standard anthropometric procedures all Expert measurements were recorded in metrics, and (3) metrics allowed for more precision in analysis and evaluation because there are no rounding or truncation errors due to unit conversions.

The statistics used are meant simple summaries of the comparisons between ARNscan and Expert. The Mean (= average) difference does not necessarily indicate whether or not the ARNscan is statistically very close to the Expert. Large positive and negative values can result in near-zero

Means. Look at the Maximum and Minimum values, too. Most important is the visual information of the chart bars and the Standard Deviation. The Standard Deviation is the range of values, plus and minus around the Mean, for two-thirds of the difference values. Thus, the Standard Deviation is a measure of the distribution of the values, either wide or narrow. Bars that are tall and mostly gathered around one point, and a small Standard Deviation, show consistency, or regularity, in the differences between ARNscan and Expert. Bars that are shorter and spread out across the chart, together with a large Standard Deviation, indicate that the ARNscan measurements differences have a large range of values, i.e., that they are not consistent with respect to the Expert.

2.1.3 Measurements

2.1.3.1 Stature (Height)
While Stature is not a direct component of any apparel item, it is used in sizing systems to specify lengths of BDU and USMC dress trousers, and the USMC coat.

Expert Definition. Height of the top of the head from the floor.

ARNscan Algorithm and Software. The definition used in ARNscan is the height in lab coordinate system of the highest point on the body scan.

There have been two challenges to accurate Stature measurement: First, there are often stray points in the scan data set which occur above the top of the scanned subject head. These points have been effectively filtered out by "decurl" tools first implemented by OU, then by Cyberware. Second, the scan data often does not record hair that can most accurately mark the top of the head. The USMC recruits who had recent haircuts were measured more accurately by the Stature software function.

The ARNscan automated Geometry stature/height function finds the highest point at the top of the head, while excluding stray points that sometimes occur in the space above the head. This and other Geometry functions use the shape characteristics of the surface points to find measurement locations without further user interaction. Observing the location of the height level while running ARNscan 7.3 showed the function to be very consistent. The variability in results, as shown below, appears to be a function of subject hair.

Results. No Expert stature measurements were taken of the subjects during T19, but only during T0 and T60. At T60, Expert stature was measured with feet together; scanning stature had the feet 30cm apart. T19 recruits who were not scanned at T60 were edited out, and the same recruits were compared for both T19 and T60 using ARN7.3. The results were good for both sets of data, but the better results with the T19 scans probably results from the shorter hair on the recruits at that point in training. Because some data are always lost in the hair, the results are consistently shorter for ARNscan versus the Expert values for each recruit. Solutions to this problem can be either a smooth cap over the hair, or an object that sits on the head and has a top a known height above it.

For ARN8, the subjects who had extreme values in ARN7.3 were analyzed satisfactorily. For the smaller sample in ARN8, the mean difference ARN8-Expert was approximately equal to that in ARN7.3. In ARN9, the tool which locates stray data points (eliminating noise above the head) was modified with the result that the top of the head for most scan data was lower than in ARN8. The lower ARN9 heights meant that they were not as close to the Expert height in 66 of 67 scans analyzed. Internally, however, ARN9 is slightly more consistent than ARN8, with a smaller standard deviation in differences with Expert values.

Visual evaluation of the graphic location of the Height measurement function shows that it is very good at accurately and consistently locating the top of the scan data set. However, the accuracy of this function is inversely correlated with the amount of hair. If recruit scans are recorded shortly after haircuts, the accuracy of ARN9 increases. Shifting the Height values up one inch will yield results very close to the Expert.

Chart 1

N	198.00
Mean	-23.71
Min	-236.00
Max	130.00
Std Dev	22.44

Height Difference (T19 Geo 7.3 - T0 Expert)

Chart 2

N	67.00
Mean	-23.81
Min	-51.00
Max	27.00
Std Dev	13.82

Height Difference, Geo 8.0

Chart 3

N	67.00
Mean	-29.12
Min	-54.00
Max	24.00
Std Dev	11.97

Height Difference, Geo 9.0
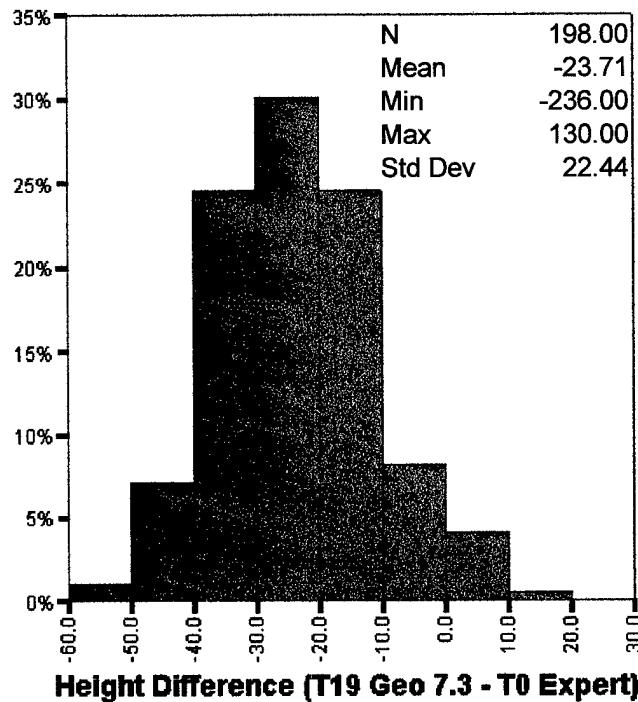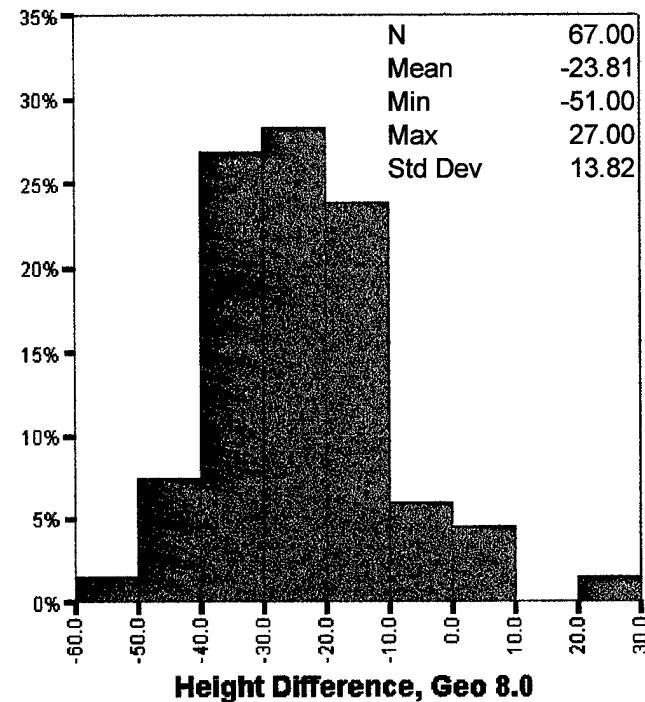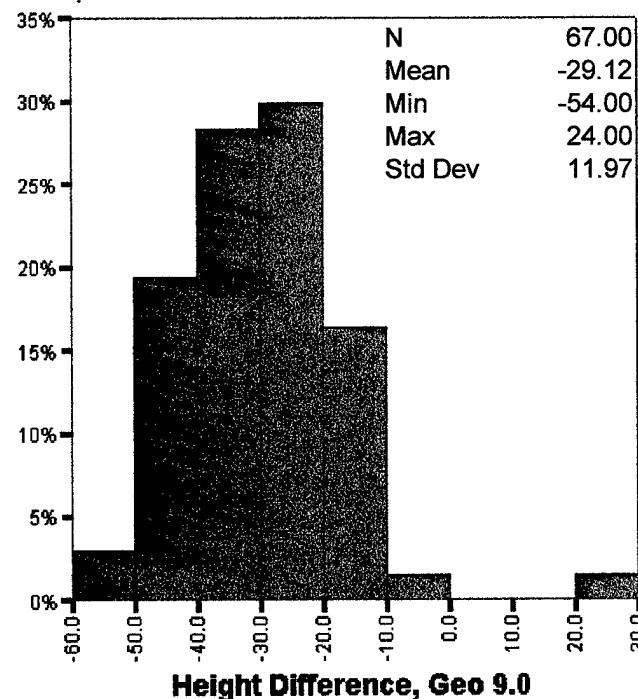
Values in Millimeters
1 Inch = 25.4mm

2.1.3.2 Neck Circumference
Neck circumference is used in sizing the USMC dress shirt.

Expert Definition. In initial meetings of all of the T2P5 Partners, several ways to measure the neck were discussed. For the clothing Partners, the neck was measured at the shirt collar level and angle. In standard anthropometry (ANSUR), the tape passes over the Adam's Apple and around the neck perpendicular to the long axis.

ARNscan Algorithms and Software. The first neck functions attempted to isolate the neck as a structure, then compute the circumference parallel to the floor at a level midway up. These failed because the neck could not be consistently isolated, and a circumference in that orientation was much larger than the Expert anthropometric measurement. The actual measurement of the circumference uses a convex hull function implemented by Cyberware. This tool takes the scan points falling on a plane, then constructs convex splines on incremental sets of three points. Finding the Adam's Apple by its shape is possible on only some people. Emulating the angle of an appropriate neck measurement also proved to be difficult, as neck posture and shape varies widely in people.

It was finally decided to implement an algorithm developed by BRC that could utilize what could be found on the neck. The algorithm is as follows:

Find the bottom of the neck
Starting at the bottom, increment the height 10mm at each iteration
   Section planes through the neck points at incremental angles
      For each plane, compute the circumference of the neck
         If, the circumference is the smallest yet found, save its value
The smallest circumference measured is the value of Neck Circumference

Consistently finding a starting point at the bottom of the neck has been the biggest challenge. In ARN7.3, two functions, Geometry (geo) and Geometry(nurre) (GeoN), were implemented. The former identifies white dots on the front. GeoN identifies dots on the side of the neck. Beginning in ARN8, Geo identifies the base of the neck through change in curvature, then computes a point location for the start of the iterative search. This has proved very consistent and permits the elimination of a dot on the scan subject.

Chart 4

N	199.00
Mean	-2.40
Min	-30.00
Max	22.00
Std Dev	7.46

Neck Circ Difference, Geo 7.3

Chart 5

N	198.00
Mean	-17.67
Min	-397.00
Max	26.00
Std Dev	72.72

Neck Circ Difference, Geo(N) 7.3

Chart 6

N	70.00
Mean	3.00
Min	-15.00
Max	23.00
Std Dev	6.44

Neck Circ Difference, Geo 8.0

Chart 7

N	212.00
Mean	1.45
Min	-23.50
Max	22.10
Std Dev	6.75

Neck Circ Difference, Geo 9.0

Values in Millimeters   1 Inch = 25.4mm

17
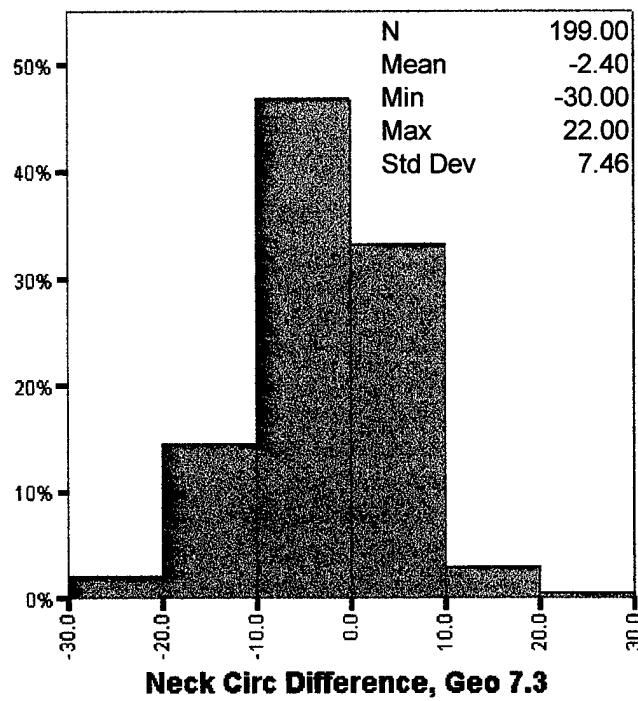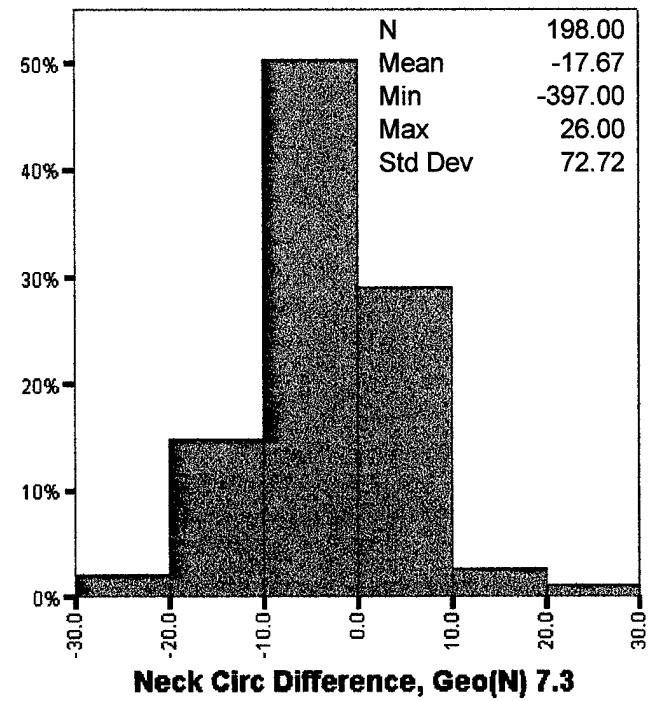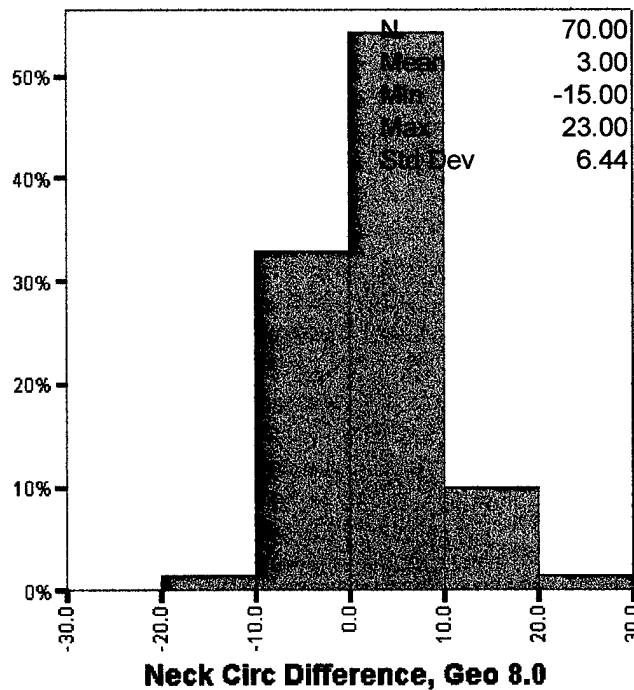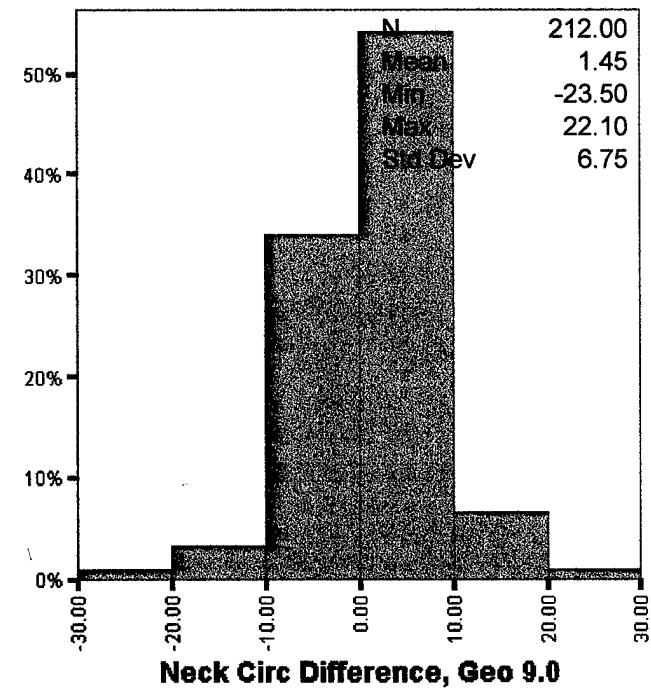
Results. While none of the Expert methods sought to measure minimum neck circumference, the results of this algorithm proved to be very consistent with the Expert values.

The results in ARN7.3 Geo and GeoN measurement functions (Charts 4 and 5) differ for two reasons: the search starting points are different and there is an occasional failure to find an appropriate neck base landmark. In the 199 scans from MCRD T19 (Session 2), landmark failure occurred twice with Geo, and six times with GeoN. Both functions yield results consistently very close to Expert measurements. The results for ARN8 Geo and ARN9 Geo (Charts 6 and 7) are even better when compared with Expert. This is the most successful measurement function in ARNscan. When the four outliers for ARN9 Geo were examined, no patterns of physical shape or software function were found. Of the two with significantly larger Geo measurements, leyb0802 has a short, thick neck, but meyr1020 appears to be average. However, the circumference on meyr1020 is drawn high on the neck. Of the two with small Geo measurements, luna0711 has a long, thin neck, but pena0109 is average.

For each scan, the ARNscan 8.0 and 9.0 were scored for which was closest to the Expert measurement value.

	Frequency	Percent
Equal	3	4.3
ARNscan8.0	38	54.3
ARNscan9.0	29	41.4

Thus, while the versions were statistically comparable, ARNscan8.0 was consistently somewhat closer to the Expert measurement value.

2.1.3.3 Chest Circumference
Chest circumference is used in sizing the USMC dress coat and shirt.

Expert Definition. There was consistency among both the clothing and anthropometry Partners on the definition of chest circumference: Circumference at the level (height above the floor) of maximum anterior point (front of the breast).

ARNscan Algorithms and Software. The automated versions of this function were implemented beginning with ARN7.3. The strategy derived from the Expert definition was to develop tools to (1) find some landmark associated with the chest in the scan data, (2) locate the correct measurement level on the chest data, and (3) accurately measure the scan data for a circumference at that level. The development to date has been an iterative process leading to full automation from initial efforts requiring user interaction. Three partners, Cyberware, OU, and BRC have worked on the software development.

The original approach by BRC was to locate the measurement point through a regression equation predicting chest circumference height from the height of the anterior scye

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landmark. Anterior scye is at the apex of the anterior axillary fold (where the underside of the arm joins the chest). This point was to be marked by a white dot on the scan subjects in the Natick Validation Study, and ARNscan software tools to automatically find this dot were to be developed. BRC asked Anthrotech to compute a regression equation using the ANSUR data that could predict chest circumference height from scye height. This equation was then included in the BRC source code. At this time, no tools to segment the scan data into arms, legs, torso, etc., had been written. We were working with a whole-body cloud of scan data consisting of all of the surface points not ordered in any way that could be of use to us in this task. In order to compute a circumference, it was necessary slice a plane through the point cloud at the chest level. When that was done, there were three cross-section areas of points: those of the right and left arms, and those of the chest. A software function was developed which extracted in sequence around the body only those points on the chest, then computed a line connecting the points with short, straight lines. The length of the line was returned as the chest circumference measurement. The points extracted to form the circumference were found in five-degree increments. Within each increment, the point closest to the center of the chest was chosen for the circumference. The result was a circumference that fit "tightly" around the data, measuring a minimal circumference. The results were mixed. The regression equation found a measurement level that was usually close to where it would have been visually chosen, but it was found that even small deviations away from the correct measurement location could result in circumference differences of several centimeters. The circumference tool functioned well, but because it drew a line tightly around the surface, it didn't emulate a tape very well in traversing gaps across the data.

For ARNscan7.3, major changes were made to the way the BRC chest circumference function worked. This was due to the work of OU in implementing a body segmentation tool, and of Cyberware in developing a chest circumference tool which use convex hulls to construct the circumference line. The OU segmentation tool automatically extracted the torso data from the whole-body point cloud, making these data available without the arms. Cyberware then developed a tool to automatically supply the approximate height for where the scye landmark should be, eliminating the need to find a dot on the body surface. BRC developed a software tool to better find the height of the chest measurement without the regression equation. This tool went back to the Expert definition that located the measurement at the height of the greatest anterior protrusion of the chest. The BRC tool started at "scye" height plus 8 cm, then incrementally worked down the chest, locating the anterior most point at each increment. The level was determined when the n+1 level did have a chest surface point that was further forward than level n:

Start at scye height + 8 cm
Find the anterior-most point in a 6 mm-thick slice of points
If the slice has a point more anterior than the last
    Save its value
Else the slice below the most anterior has been found
   End the search and use the last slice to compute the circumference

Also for ARNscan7.3, BRC used the convex hull tools developed by Cyberware to actually measure the circumference on the points that had been formerly used for the "tight" circumference.

In ARNscan7.3, Cyberware also developed a chest circumference function that sought to find the measurement level using an algorithm similar to that of BRC.

In ARNscan8.0, a new body segmentation tool was developed by Cyberware to replace that of OU. While the OU tool found the border between arms and torso by following the gaps up into the axilla, the Cyberware tool uses bounding boxes to section the body segments. The result is effective, but the bounding box has a tendency to "shave" off the sides of the torso in some individuals, reducing the point cloud surface used to measure circumferences. This has been improved in ARNscan9.0. In ARNscan8.0 Cyberware also modified the chest measurement level function, greatly improving its accuracy. BRC modified its use of the point cloud to reduce errors due to missing data.

Chart 8
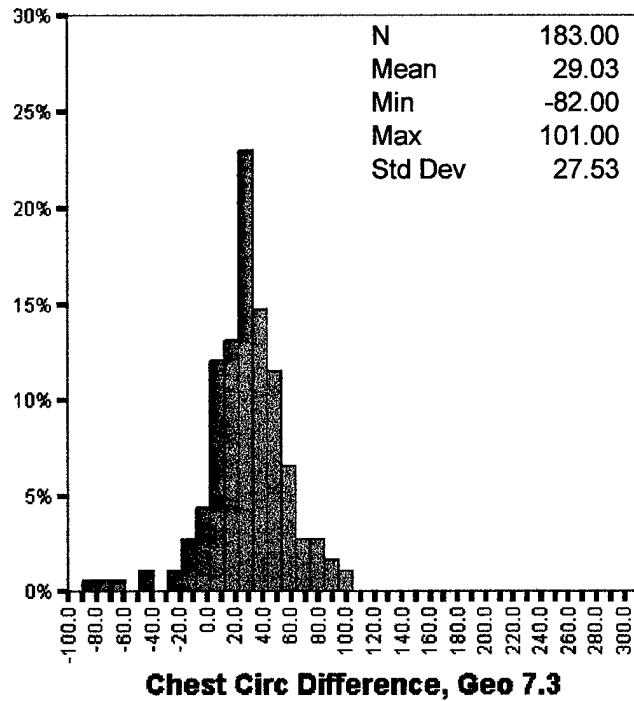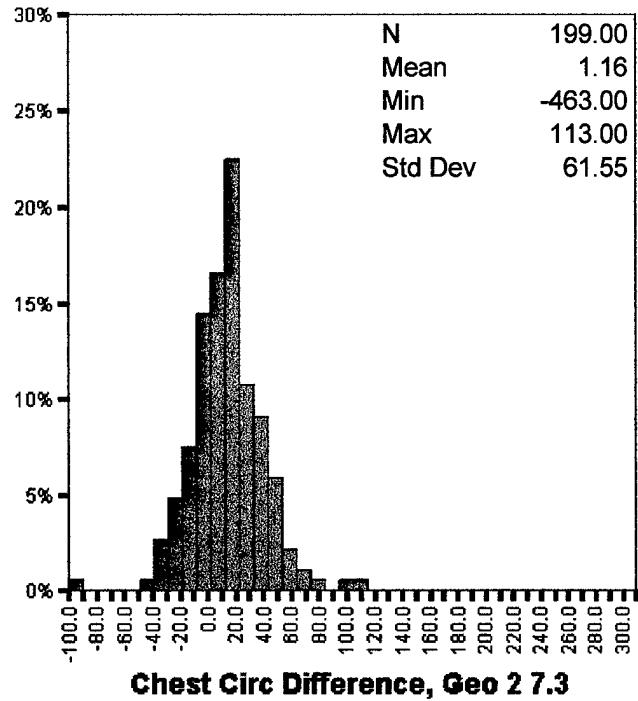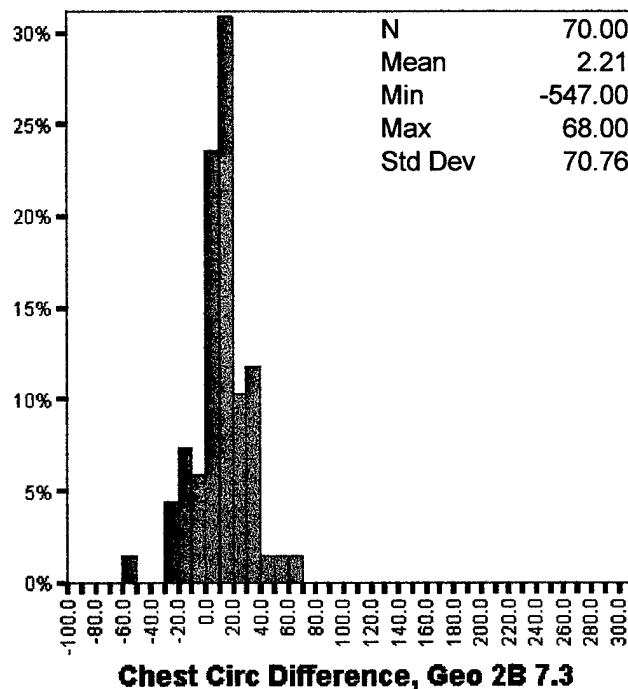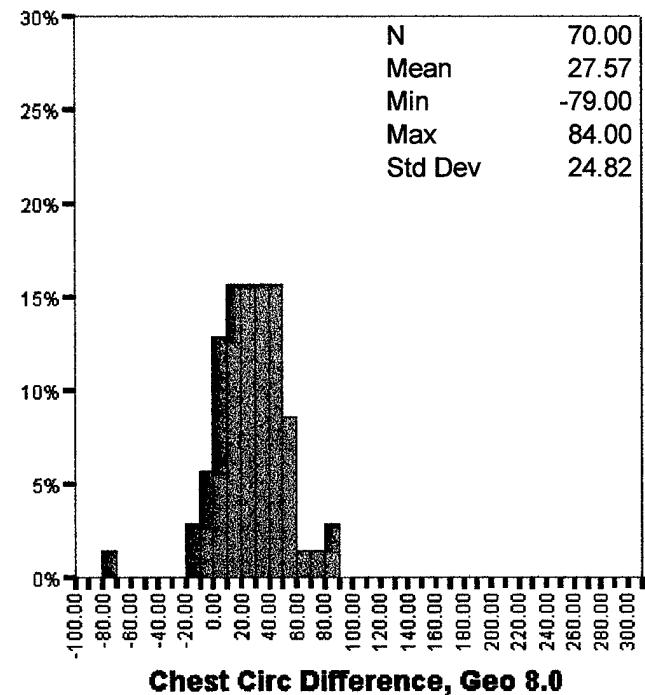
N	183.00
Mean	29.03
Min	-82.00
Max	101.00
Std Dev	27.53

Chest Circ Difference, Geo 7.3

Chart 9

N	199.00
Mean	1.16
Min	-463.00
Max	113.00
Std Dev	61.55

Chest Circ Difference, Geo 2 7.3

Values in Millimeters   1 Inch = 25.4mm

Chart 10

N	70.00
Mean	2.21
Min	-547.00
Max	68.00
Std Dev	70.76

Chest Circ Difference, Geo 2B 7.3

Chart 11

N	70.00
Mean	27.57
Min	-79.00
Max	84.00
Std Dev	24.82

Chest Circ Difference, Geo 8.0

Values in Millimeters   1 Inch = 25.4mm
Chart 12

N	197.00
Mean	15.32
Min	-77.00
Max	303.00
Std Dev	51.75

Chest Circ Difference, Geo 2 8.0

Chart 13

N	212.00
Mean	25.05
Min	-97.70
Max	82.70
Std Dev	26.15

Chest Circ Difference, Geo 9.0
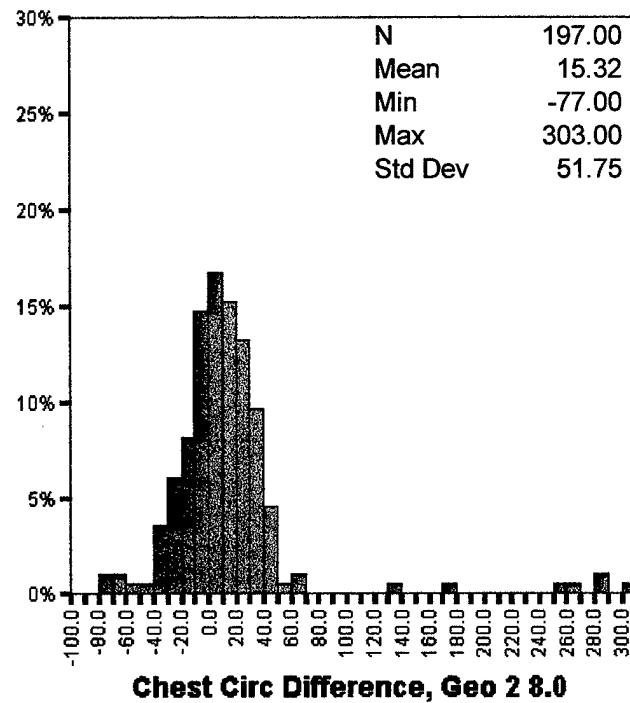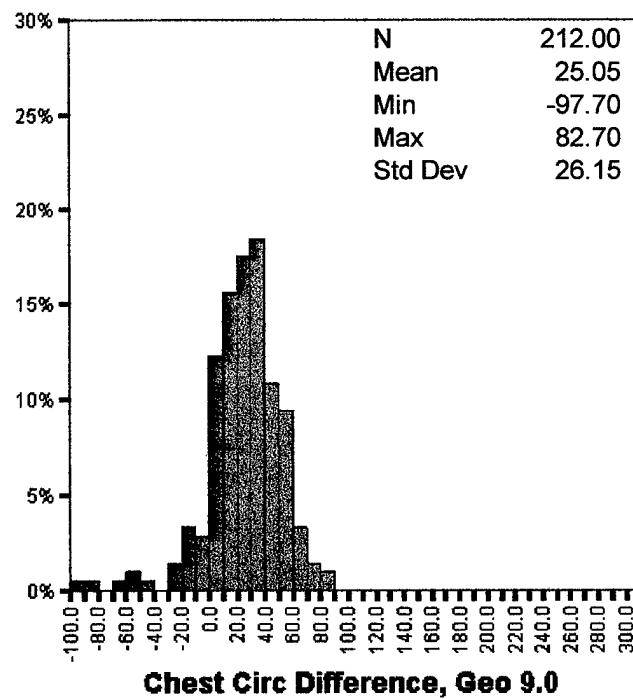
Algorithm Closest To Expert Chest Circumference: ARNscan8.0 Geo vs. ARNscan9.0 Geo

	Frequency	Percent
Equal	7	10.0
ARNscan8.0 Geo	34	48.6
ARNscan9.0 Geo	29	41.4

Algorithm Closest To Expert Chest Circumference: ARNscan8.0 Geo2 vs. ARNscan9.0 Geo

	Frequency	Percent
ARNscan8.0 Geo2	149	76
ARNscan9.0 Geo	47	24

Results. Six sets of results will be discussed, reflecting differences in body segmentation tools, measurement location tools, and circumference measurement tools in ARNscan 7.3, 8.0, and 9.0.

Two ARNscan7.3 functions were used to measure the MCRD T19 recruit scans for Chest Circumference, defined as a circumference at the level of maximum protrusion of the chest. The first was the Geometry function developed by Cyberware already in version 7.3 (Geo 7.3). The second was a BRC function ported from ARNscan 6.2 code and designated Geometry2 (Geo2 7.3, using what was called in earlier versions the Predict code). Both functions use an iterative search and measure procedure to find the appropriate level (height) for measuring Chest Circumference, and both use the same convex hull tools to measure the circumference. The difference is in the procedure for determining chest height, and extracting the points at that level to be measured. It was found that the Geometry2 tools for finding chest height are more accurate, but that the Geometry function used a more reliable method to extract the points to be measured. When the two functions were used to measure Natick validation data sets, the same results were reached.

Charts 8 and 9 display frequency distributions for the differences between ARNscan7.3 and Expert chest measurements for each of the MCRD T19 scans. Eleven of the scans measured by Geo7.3 were noted as having chest heights at least two inches higher or lower. The result is that circumferences taken with this value are more often larger than Expert (Tape) measurements for the subject's chest. Notice on Chart 8, graphing the difference Geo7.3 minus Expert for each scan, that most of the values are positive, resulting from the larger Geo7.3 values. On the other hand, incomplete point sets extracted by the Geo2 function resulted in poor circumference measurements for 14 of the 201 scans. Notice on Chart 9 that several of the values are extremely negative, resulting from incompletely drawn circumferences by Geo2. Examining the individual scan results, the Geo2 function is including a point on the inner surface of one or both arms in several other scans, thus extending the circumference out from the chest surface for subjects with values of Geo2 minus Expert greater than 60mm. For other large values, there is no graphic indication of any ARNscan measuring problem. Without the

poor results scans, the measurements at the level found by Geo2 are significantly more consistent with Expert measurements. The comparable summary statistics for the difference values were Mean = 13.7, Standard Deviation = 22.2, Minimum Difference = -40, Maximum Difference = 79.

Because the inconsistency in Geo2 made the function unacceptable, modifications were made to reduce the errors and improve the accuracy with respect to Expert measurement values. Geo2 uses the entire body scan data set, including the arms, to extract the Chest circumference. Therefore, the function was written to draw the circumference "under" the arms as it passes between them and the torso. The function was changed so that it operates only on the torso data after body segmentation. This allowed for a more robust and consistent search for torso circumference points, greatly improving the results. The new function was designated Geometry2B (Geo2B7.3). Using Geo2B, one scan measurement out of 70 was a total failure due to a problem in finding the scye point from where the search for chest height stars. Four circumferences had small errors due to be being incompletely drawn. Chart 10 shows visually that a far higher percentage of scans were closer to the Expert value than either Geo7.3 or Geo2 7.3, or Chest tools developed for ARNscan 8.0 or 9.0. Without the failed scan subject, the summary statistics for Geo2B would be Mean 10.0, Standard Deviation 24.1, Minimum Difference -104, Maximum Difference = 68.

In ARNscan8.0, the Geometry (Geo8) chest height location tool was changed by Cyberware and was much more accurate. The circumference-measuring tool is the same as Geo7.3. However, the segmentation tool was changed in ARNscan8.0, which resulted in new problems for accurate measurement. The ARNscan8.0 segmentation tool used a Bounding Box to enclose the body segments. For the torso, this resulted in "shaving" off parts of the sides, depending on body build. These shaved areas were then assigned to right and left arms, instead of the torso. The resulting torso data are missing side points, and the circumference is cut short by the loss. This was observed to occur in 18 of 70 scans (26%). Because the Geo8 chest values were usually larger than the Expert, the segmentation errors usually improved the result for individuals, but increased the standard deviation for the group (Chart 11). However, this segmentation error is unpredictable and would probably be more pronounced with more diverse body types.

In evaluating the results using ARNscan8.0 Geometry and ARNscan7.3 Geometry2B (Geo28 in ARNscan8.0), both are improvements over their predecessors (see the data file for results). In the summary statistics of the differences ARN-minus-Expert values, Geo28 is better using both the real (plus and minus) and absolute values for the differences. Likewise, when individual cases of ARN-minus-Expert values are compared, Geo28 is closer to the Expert (nearer 0) in 54 of 70 cases (77%). This seems to result mostly from the use of an inner, or minimal, hull circumference approach in Geo28, versus the outer hull used in 8.0 Geometry. When viewed graphically, there is no obvious systematic error in either circumference tool. However, Geo28 in ARNscan8.0 did not work well because of the new segmentation problems (Chart 12). Here, the problem was that segmentation between arms and torso occurred lower on the arms than the intended scye landmark in 7 of 197 scans measured, resulting in a "Venus di Milo"

effect. This caused the circumference to be drawn over the arm "stumps" in several cases.

The ARNscan9.0 Chest Circumference-Geometry (Geo9) function is identical to that used in ARNscan8.0. The modification of the body segmentation tool for ARNscan9.0 resulted in some small differences in performance (Chart 13 versus Chart 11). In ARNscan8.0 we evaluated two functions: The Cyberware Geo8 which has been retained for ARNscan9.0, and a BRC function Geometry2 (Geo28). As was noted in the evaluation of ARNscan8.0, Geo28 measurements are closer to traditional values than Geo8. Likewise, Geo28 is more consistently closer than ARNscan9 (76% to 24%), and has 20% fewer outliers (scan measurements differing from Expert by more than one inch). The results reflect the better performance of Geo28 in finding the proper height at which to take the Chest Circumference. Most errors in Geo9 are in locating the height too low because of a sloping chest on the subject. Also, continuing errors in segmentation cut out points on the side of the chest in many scans, also reducing accuracy when compared with ARNscan7.3.

The segmentation tool in ARNscan7.3 is clearly superior for the purposes of measuring chest circumference. For the circumference tool, the outer hull measurement with more accurate chest height location is still not as close to Expert values as either ARNscan7.3 Geometry2 or Geometry2B using inner hulls. However, with real values having nearly identical standard deviation, the relative performance of ARNscan8.0 and 9.0 may be substantially improved by simply shifting all values down by, say, 25mm (~1 inch).

2.1.3.4 Waist Circumference
Waist Circumference is used in size selection for the USMC trousers and dress coat.

Expert Definitions. Waist circumference is measured horizontally, but the height at which it is taken can be defined several ways. Standard anthropometric definitions for the location include (1) maximum indentation of the side, (2) omphalion (naval), and the (3) preferred height of the subject. For the Natick Validation study, we used preferred waist height. For the MCRD project, we used the Marine definition: immediately above the top of the hip (iliocristale).

ARNscan Algorithms and Software. The changing definitions of the waist meant that there were changes in the algorithms and software code that located the height and measured the circumference itself. Without a target application until work began with the Marines, the T2P5 partners decided that preferred waist would be the best definition for use in the Natick Validation. Because this would require a visible landmark to be applied to the subject, no other work seeking to automate waist height location was done until after the Natick project.

Thus there were two ways to find the waist height when the Natick scans were measured: (1) cursor-picking a point where the white dot applied to the subject was visible, or (2) using the landmark locating tool developed by Cyberware to automatically find the dot. Neither was deemed satisfactory as a long-term solution. The manual method required

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operator intervention, and the dot-locator was not consistently successful. BRC decided that the only satisfactory automated solution lay in being able to predict waist height from regression equations utilizing other measurement data: Stature, Chest Height, and Seat Height. All of these measurements were becoming very consistent and automated.

When the MCRD recruits were prepared for scanning, a white dot was placed on their chest six inches above the specified location for the Marine dress trousers. The dot was located high so that it could be seen or automatically recognized apart from the white underwear of the recruits. When ARNscan 7.3 was released after the MCRD scanning, Cyberware included several new waist location functions. These functions were all based on body shape, but were intended to approximate the true location of the Marine waist. BRC modified the program so that the waist heights computed by these functions would be written out and also graphically displayed on the recruit scan data. None of the functions proved consistently reliable in matching actual waist height. BRC made two additional modifications to ARNscan 7.3 with respect to the waist height. First, the manual cursor-picking function was changed so that the location for the waist measurement would be six inches below the picked dot – the true waist height. Second, in order to compute a regression equation predicting waist height, each recruit's Stature, Chest Height, Seat Height, and picked Waist Height were automatically written out for analysis. The data from the MCRD scans were used to compute the equation

Waist Height = Seat Height * 0.000474 + Chest Height * 0.000383 + Stature * 0.094 + 0.045751

The input units are in millimeters, output in meters. When used to predict MCRD waist heights, the average error was close to 0.0, with a standard deviation 17.0 mm (~2/3 inch). The regression analysis is attached as an Appendix.

While the predicted waist height function was developed and tested in ARNscan 7.3, using best available stature, chest height, and seat height functions, new functions for these measurements were implemented by Cyberware by ARNscan 9.0. This necessitated modification of the regression equation, which Cyberware did and tested.

The circumference algorithms and software in ARNscan 7.3, 8.0, and 9.0 were the same convex hull tools developed by Cyberware.

Results. Charts 14-17 compare results for four versions of the waist circumference function. All four, however, measure circumference using the same convex hull software tool. Different waist height location and body segmentation tools affected the results.

Chart 14 shows the distribution of differences between ARNscan 7.3 Waist-Geometry and Expert measurements for all T19 recruits. The Geometry function used here found waist height by searching for the most anterior point (greatest indentation) on the back at the lumbar curve. The Manual, Predicted 8.0 and Predicted 9.0 all measure the waist at or near the actual Marine waist height. The Predicted versions differed in the versions of the tools used for values used in the regression equation (Stature, Chest Height, and Seat

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Height), but the results are comparable. With the Manual, the waist height was cursor-indicated by the user, and so the height is known to be accurate.

While the location for Waist measurement is accurate using the Predicted versions, the results are that there are still 20% of the measurements +/- one inch different from the Expert values, with most errors on the plus side. Simply subtracting the Mean value reduces these errors to about 15%. In reviewing the scans and measurements graphically, it appears that the errors may be due to measurement techniques. The ARNscan measurement goes over any fat or bulges around the waist. It may be that the tape sometimes compresses the fat resulting in a measurement smaller than that from ARNscan.

Chart 14

N 199
Mean 4.2
Min -79
Max 248
Std Dev 26.5

Waist Circ Difference, Geo 7.3

Chart 15

N 198
Mean 5.8
Min -33
Max 80
Std Dev 18.5

Waist Circ Difference, Manual 7.3

Values in Millimeters   1 Inch = 25.4mm

Chart 16

N 70
Mean 13.6
Min -42
Max 60
Std Dev 17.4

Waist Circ Difference, Predicted 8.0

Chart 17

N 70
Mean 10.6
Min -52
Max 69
Std Dev 16.3

Waist Circ Difference, Predicted 9.0

28
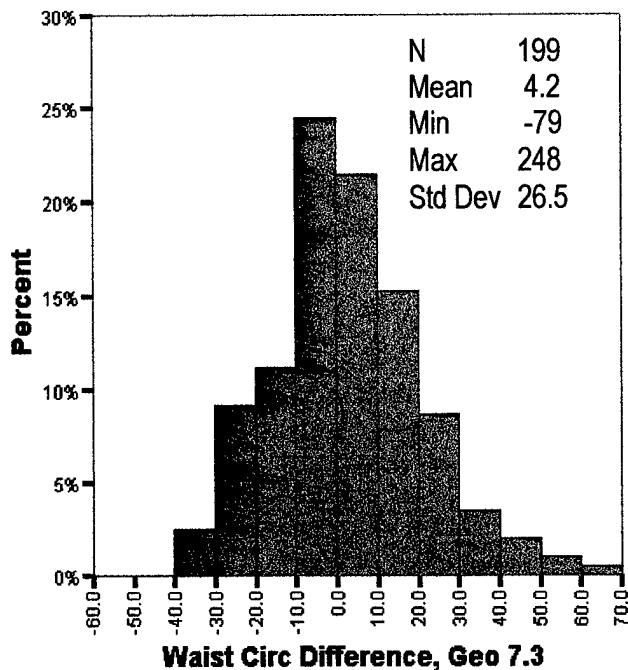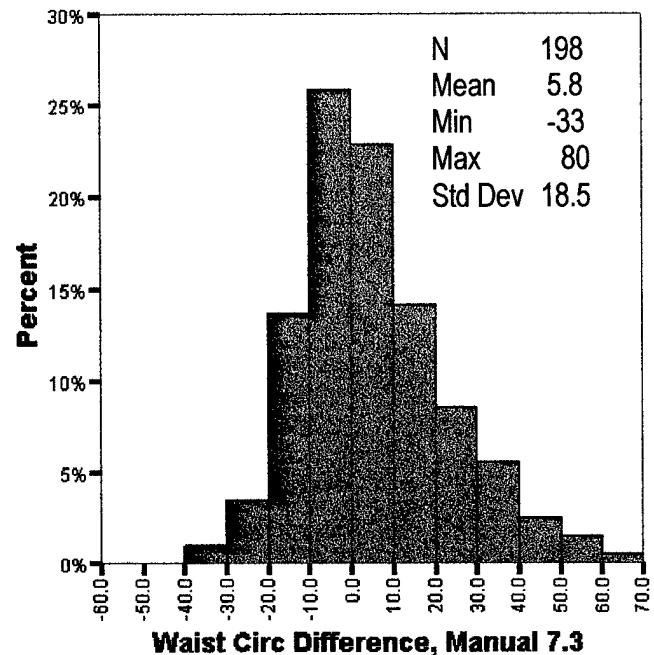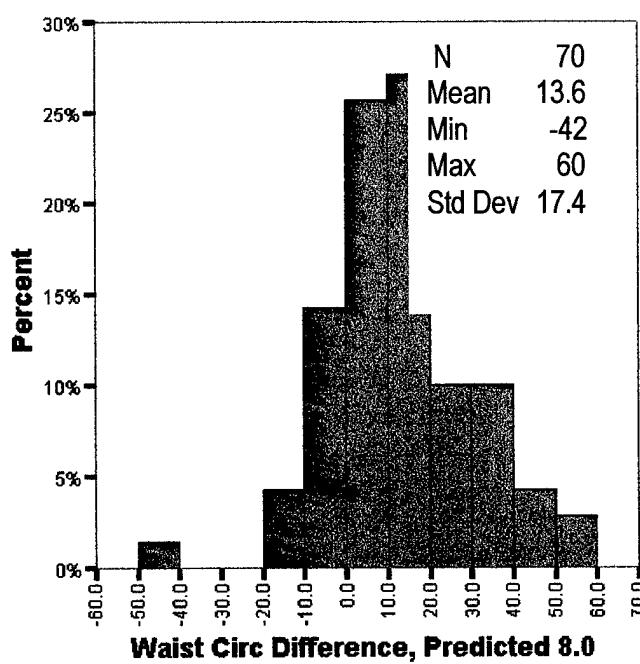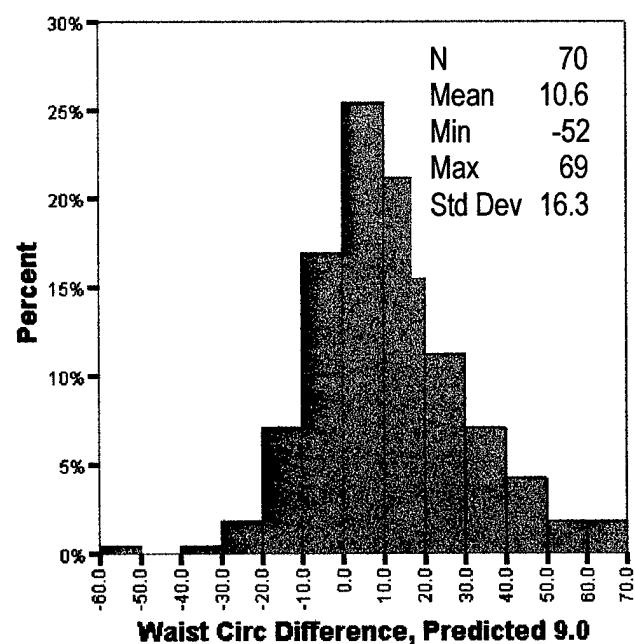
2.1.3.5 Seat Circumference
Seat Circumference is used in sizing the USMC dress coat and trousers.

Expert Definition. The horizontal circumference at the level of the maximum posterior point on the buttocks.

ARNscan Algorithms and Software. The history of algorithm development for this measurement was simple. Automating the location of seat circumference level was accomplished by taking cross-sections of the pelvis at successively higher levels beginning at the crotch at ending at the waist. At each level, the maximum posterior point was found. At the level where that point was most posterior, the circumference was measured around the point cloud. The only modifications necessary in this process were to keep the search area below the waist. This algorithm was created by BRC. Some subjects had fat around the waist ("spare tires") which actually protruded posterior to a flat buttocks, resulting in an incorrect location for seat circumference level. In ARNscan9, Cyberware modified the search procedure by increasing the incremental heights for the test cross-sections, speeding up the search. This resulted in some differences in results for ARNscan8 versus ARNscan9.

The circumference was measured, beginning in ARNscan7, exclusively using the convex hull tool.

Results. There are some very real differences between results for ARNscan 8.0 and 9.0. Chart 19 illustrates that the differences between ARNscan8.0 and the Expert are relatively few using that version (note the 8.6mm standard deviation). Chart 20 shows that the modification of the Seat function to increase speed results in a degradation of performance, too. In comparing the consistency of the two versions with Expert values,

Algorithm Closest To Expert Seat Circumference: ARNscan8.0 vs. ARNscan9.0

|	Frequency	Percent
ARNscan8.0	65	93
ARNscan9.0 Geo	5	7

In addition, ARNscan 8.0 resulted in 61% fewer measurement differences +/- one inch. The ARNscan8.0 mean difference from Expert of 0.18" and standard deviation of approximately 1/3" makes it one of the most consistent software functions when compared with tape measurements.

Chart 18   **Chart 19**

N	199
Mean	25.65
Min	-27.00
Max	79.00
Std Dev	15.96

Seat Circ Difference, Geo 7.3

N	70
Mean	4.73
Min	-22.00
Max	47.00
Std Dev	8.63

Seat Circ Difference, Geo 8.0

Values in Millimeters   1 Inch = 25.4mm

Chart 20

N	212
Mean	31.98
Min	-32.00
Max	94.30
Std Dev	17.02
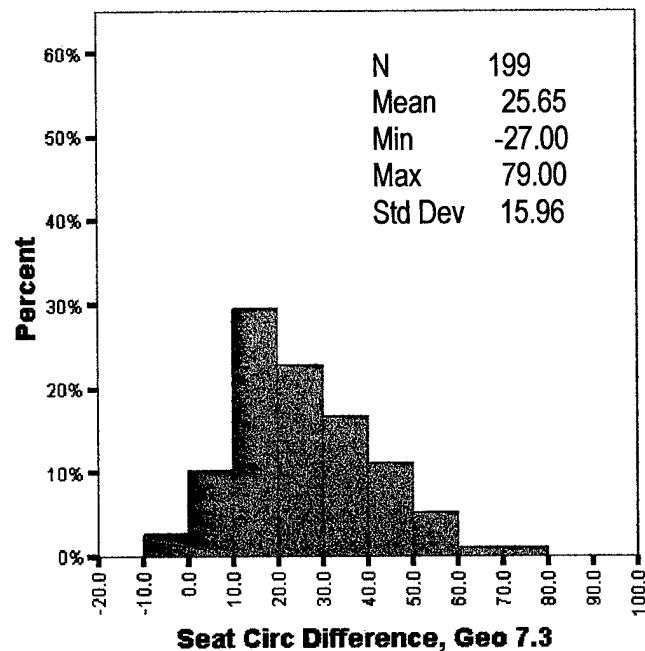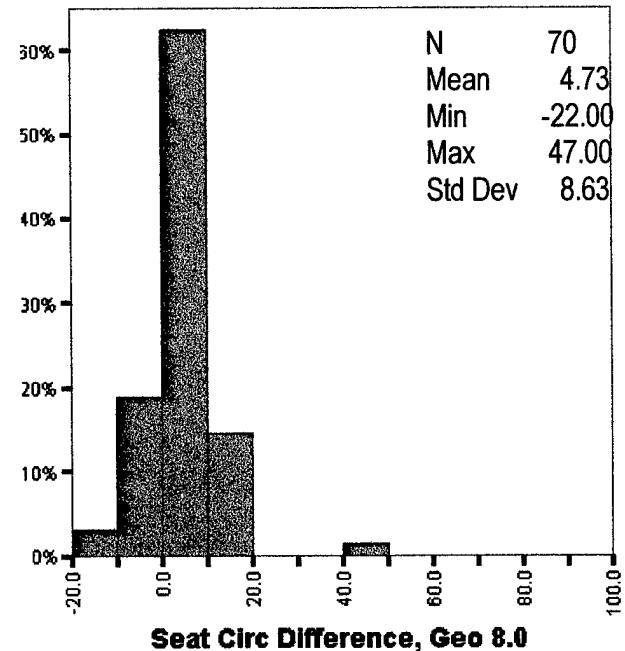
Seat Circ Difference, Geo 9.0
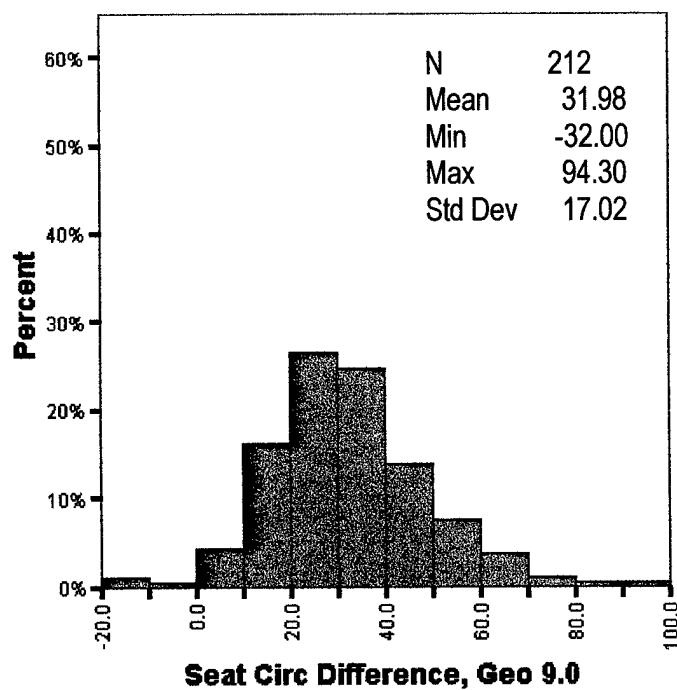
2.1.3.6 Cross Shoulder

Cross Shoulder is used to size the Marine dress coat.

Expert Definition. Cross Shoulder is a surface measurement for the distance between the lateral edges of the shoulders. The path that the tape follows across the shoulders differs among clothing personnel. There is no equivalent standard anthropometric measurement, so the definition adopted for use here was the minimum tape distance between right and left acromion landmarks.

ARNscan Algorithms and Software. The definition used in ARNscan was the minimum surface distance between shoulder endpoints. Shoulder endpoints were defined differently for different versions of this tool. The first algorithm to find the endpoints was developed by Ohio University (OU) and implemented in ARNscan7.3.

The principal difference between the Cross-Shoulder-Geometry functions in ARNscan 7.3 and ARNscan 8.0 and 9.0 is in the automated location of the endpoints on the shoulders used for the measurement. ARNscan 7.3 uses a profiling function to measure change of curvature at the edge of the shoulder. ARNscan 8.0/9.0 uses bounding boxes to isolate the shoulder edge region, then finds endpoints by iteratively moving angled planes toward the surface edge of the shoulder until "surfacing". After the endpoints have been found, surface contours are constructed across the back of the shoulders along planes of increasing elevation. The shortest surface contour connecting the two end-points is the Cross-Shoulder. This algorithm was created by BRC.

In support of Carol Ring's USMC size selection work, BRC experimented with several modifications in the Cross Shoulder function code. Despite numerous efforts to reduce or eliminate known errors in the results, it was decided that the current software was as good as any other efforts.

Results. The two tools are statistically similar in their results. Examining the recruits graphically using the 8.0 tool, no unusual patterns were seen.

The fact that neither software tool actually locates the acromion landmarks used for the Expert measurements means that it is impossible to accurately evaluate the results by comparisons. The fact that most, but not all, of the ARNscan values are larger than the traditional suggests that the tools find end-points usually outside of the actually acromions. Where the ARNscan values are smaller than the Expert, it is not clear why that happens. Some errors were visible in the form of endpoints obviously to wide or narrow, but again there was no obvious correlation with any shoulder shape characteristics.

The ARNscan 8.0 tool appears to be as consistent as in 7.3. The results are different for individuals, however, and should be tested in the size selection rules. That test may show a preference for one tool over the other. The difference results in Charts 21-23 illustrate that statistically the available tools are as good as other ARNscan measurements.

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However, proper sizing requires more accuracy than may be necessary from other measurements.

Values in Millimeters   1 Inch = 25.4mm

Chart 21

N	196.00
Mean	15.18
Min	-48.00
Max	92.00
Std Dev	18.16

Cross Shoulder Difference, Geo 7.3

Chart 22

N	70.00
Mean	14.67
Min	-20.00
Max	45.00
Std Dev	14.77

Cross Shoulder Difference, Geo 8.0

Chart 23

N	212.00
Mean	16.06
Min	-43.40
Max	73.30
Std Dev	18.24

Cross Shoulder Difference, Geo 9.0

Chart 24

N	146.00
Mean	-4.35
Min	-53.70
Max	87.10
Std Dev	22.70

Cross Shoulder Difference, Landmark 9.0
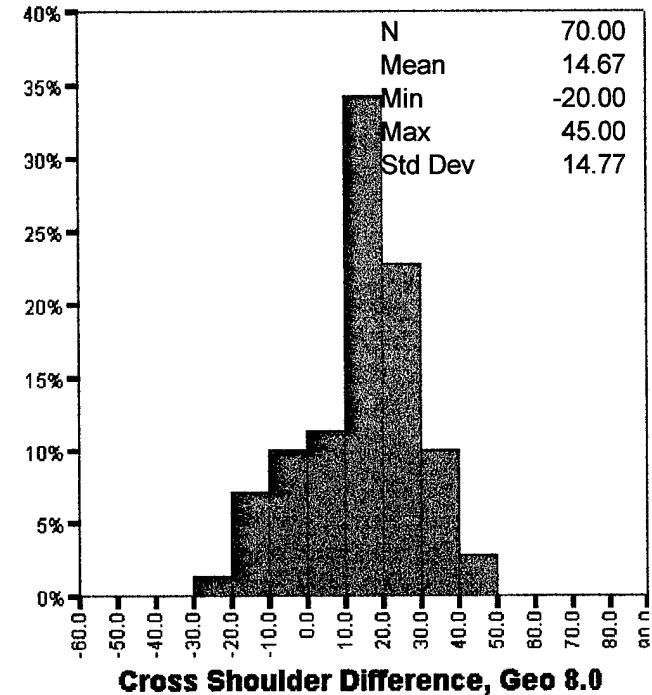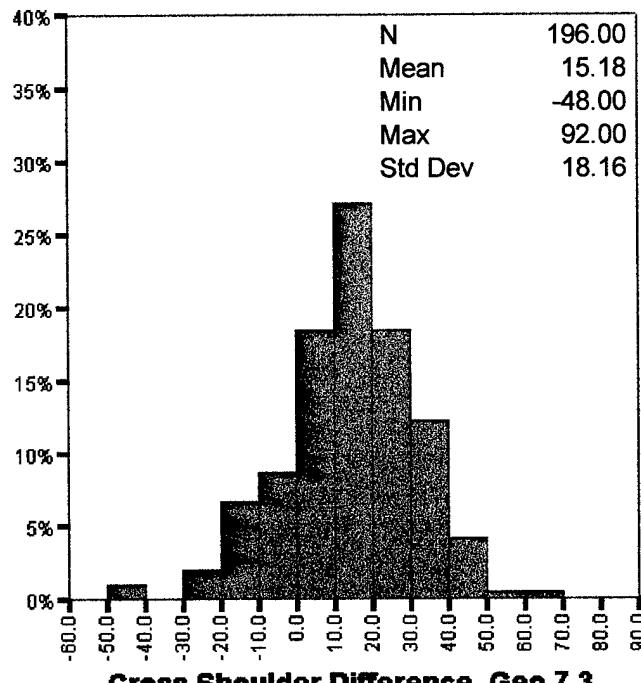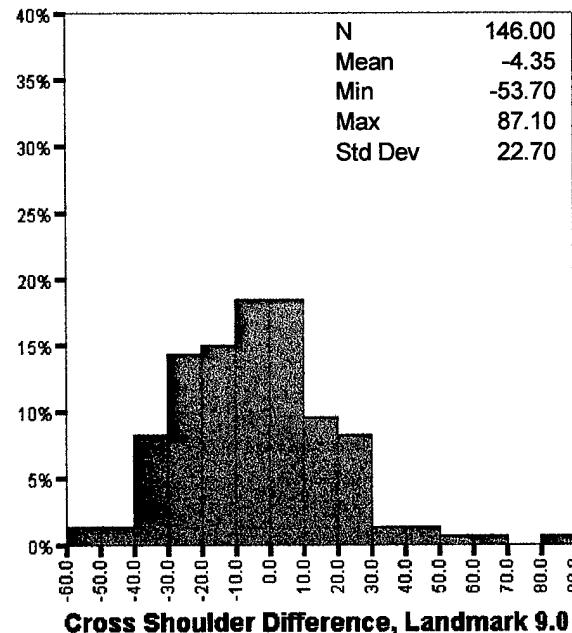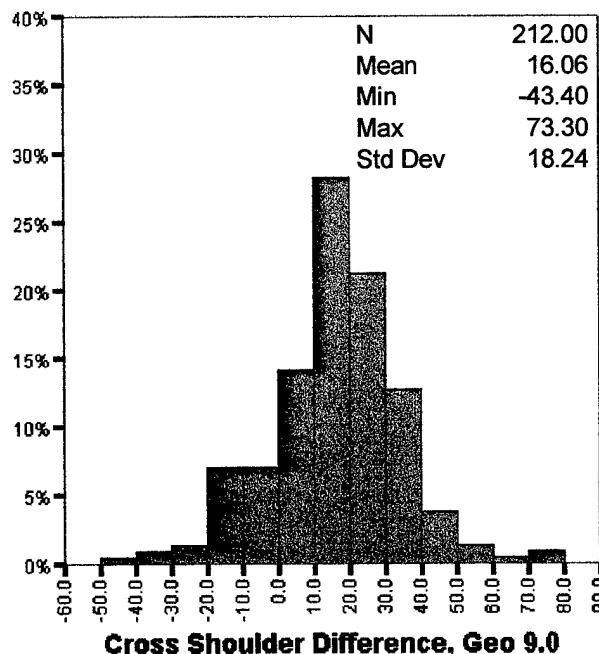
2.1.3.7 Sleeve Length

Sleeve Length is used to size the Marine dress Shirt.

Expert Definition. The definition of this measurement was the source of much variation amongst the clothing personnel. The original definitions varied in where the measurement started on the back, and how it passed over the shoulder. The Marine Sleeve Length was defined by SPSU as starting at the cervicale landmark at the base of the neck, then passing over the acromion and down the arm to a point one inch above the base of the thumb.

ARNscan Algorithms and Software. ARNscan 7.3-9.0 Sleeve Length is defined as one-half Cross-Shoulder plus the straight-line distance from the Right Shoulder Point ("Acromion"), to the Right Wrist. In ARNscan 8.0, a new Cross-Shoulder tool is combined with the arm outseam length tool from ARNscan 7.3. The tools to locate the wrist endpoint in ARNscan7.3 and 8.0 found the smallest circumference as the endpoint. ARNscan9.0 used the prominence of the thumb as a landmark.

Results. The biggest problem has been the inconsistency with which the tool locates the wrist. The location is often fixed at 1-2 inches above (proximal to) the wrist when we look at the results graphically in ARNscan 7.3/8.0. Less often, the tool locates the wrist at the base of the fingers (metacarpal-phalangeal, or MP, joints). The wrist locator in ARNscan9.0 proved to be much more accurate. ARNscan9.0 had 75% fewer errors +/- one inch when compared with ARNscan8.0. Statistically, however, ARNscan8.0 was more accurate for the fewer subjects evaluated. Because Sleeve Length requires some precision, this inconsistency makes it difficult to apply to size selection for the shirt. Carol Ring (SPSU) has noted that the shirt sleeve length can be a little longer than necessary, but cannot be too short.

ARNscan9.0 is a great improvement over ARNscan8.0 in that it attempts to locate a point on the thumb near where the sleeve end was marked on the scan subjects, rather than the wrist. The point located by ARNscan9.0 is the anterior-most point on the hand. With the palm facing inward, that point is often the base of the thumb, where the sleeve end is. The shoulder point is that used as an end point by Cross Shoulder-Geometry.

The strength of this tool is that the sleeve end point is at least approximated more consistently than with any other tool. At the most, it misses the dot on the hand by about two inches. We examined the results graphically, and found that in 66.1% of the scans, Geo9 found the correct sleeve end point. In 27.3%, the end point was too short, and in 6.6%, it was too long. We recommend that different hand posture be used to increase the accuracy of this tool in locating the correct sleeve end. Errors in these scans seemed to result mostly from individual hand shapes, rather than the posture. One suggestion is the Marine hand position at attention. Accuracy would also be improved if the Sleeve Outseam were a surface measurement rather than straight-line point-to-point. When we examined the sleeve outseam outliers, the most common problem (other than errors at the

sleeve end) were in computing a length too short. The cause of this was the fact that the straight-line cut through part of the upper arm, rather than following the surface.

Chart 25
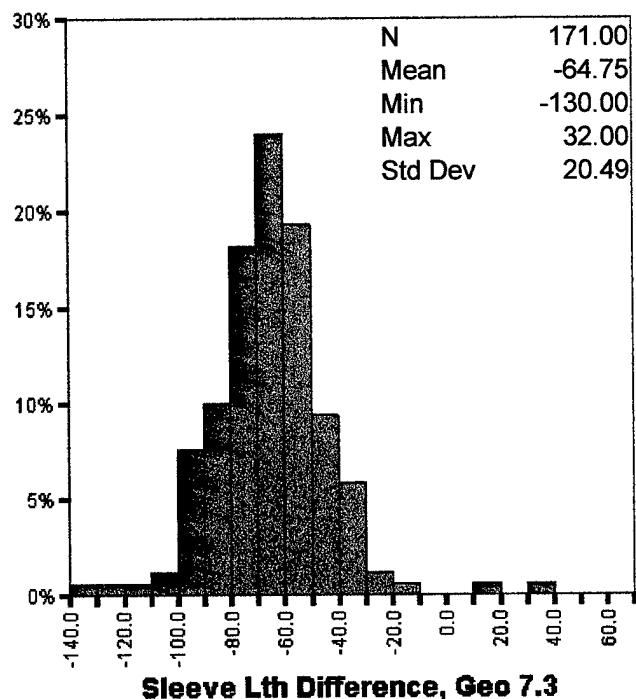
N	171.00
Mean	-64.75
Min	-130.00
Max	32.00
Std Dev	20.49

Sleeve Lth Difference, Geo 7.3

Chart 26

N	70.00
Mean	-60.39
Min	-124.00
Max	45.50
Std Dev	37.86

Sleeve Lth Difference, Geo 8.0

Chart 27

N	195.00
Mean	-1.48
Min	-65.40
Max	60.30
Std Dev	16.22
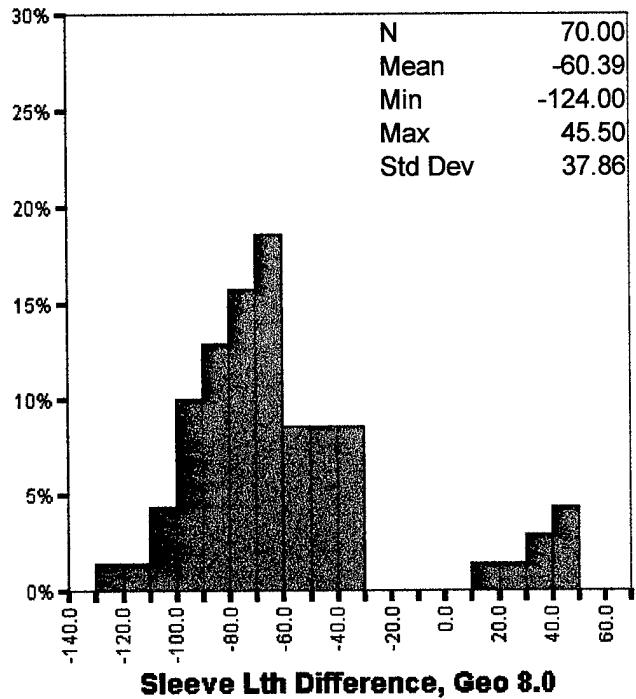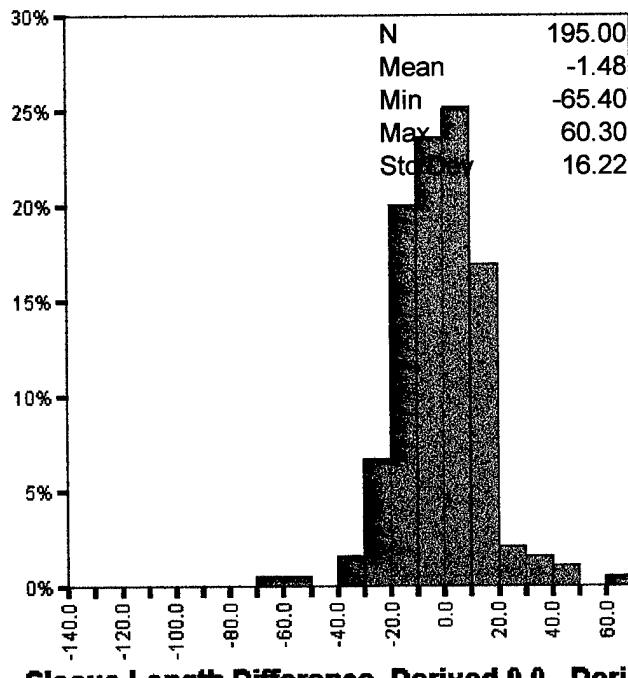
Sleeve Length Difference, Derived 9.0 - Deriv

Values in Millimeters
1 Inch = 25.4mm

36

2.1.3.8 Pant Inseam

Pant Inseam is used to size the Marine dress trousers.

Expert Definition. Clothing personnel measure this as the end of the cuff to the bottom of the trouser crotch.

ARNscan Algorithm and Software. The simplest approximation of the clothing definition is to measure crotch height – the straight height above the floor of the lowest crotch point. It was thought that this measurement would be similar to true inseam length because the subjects were being measured with feet 30cm apart – shortening the measurement. This algorithm was created by BRC. The software was automated by OU in the first automated segmentation release for ARNscan7.3. Here, the legs were separated from the torso at the crotch, and so that height was used as the Inseam measurement value.

Results. Because the measurement value is the height of segmentation between legs and torso, the accuracy has been dependent on the consistency of the segmentation tools. As can be seen in Charts 28-30, OU segmentation tools in ARNscan7.3 was more accurate than ARNscan8.0, which had a Cyberware segmentation tool. ARNscan9.0 is more accurate than either earlier version, with an average difference from Expert of –0.25", and only 10 subject errors +/- one inch.

Chart 28

N	195.00
Mean	6.58
Min	-65.00
Max	31.00
Std D	9.19

Inseam Difference, Geo 7.3

Chart 29

N	70.00
Mean	-9.73
Min	-49.00
Max	15.00
Std Dev	13.96

Inseam Difference, Geo 8.0

Chart 30

N	212.00
Mean	-6.11
Min	-48.00
	27.00
ev	9.51

Inseam Difference, Geo 9.0

Values in Millimeters
1 Inch = 25.4mm

38
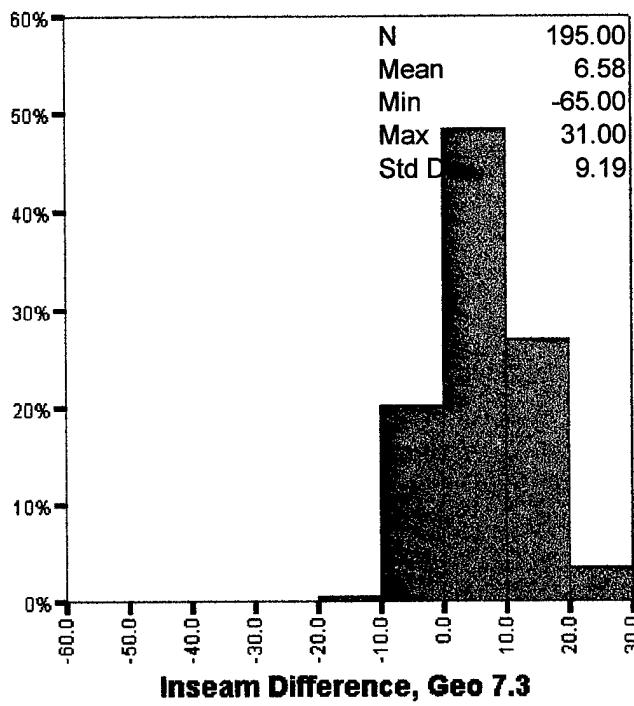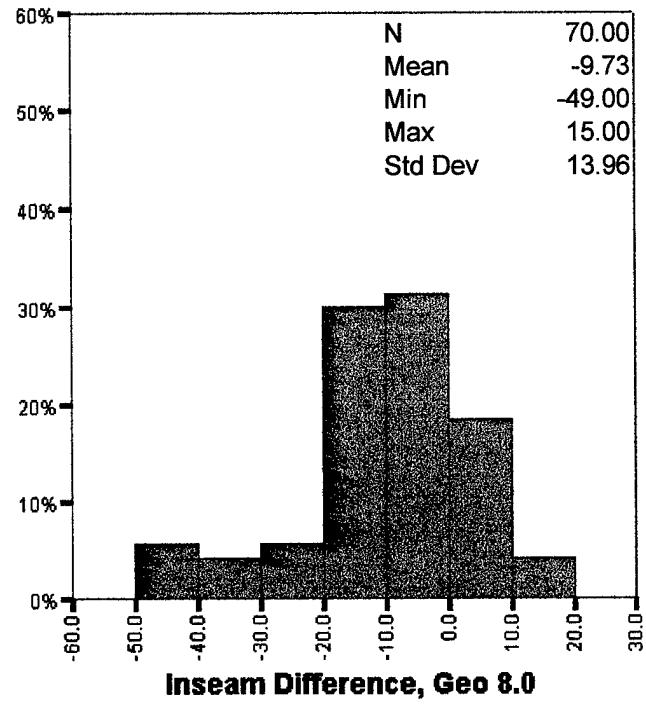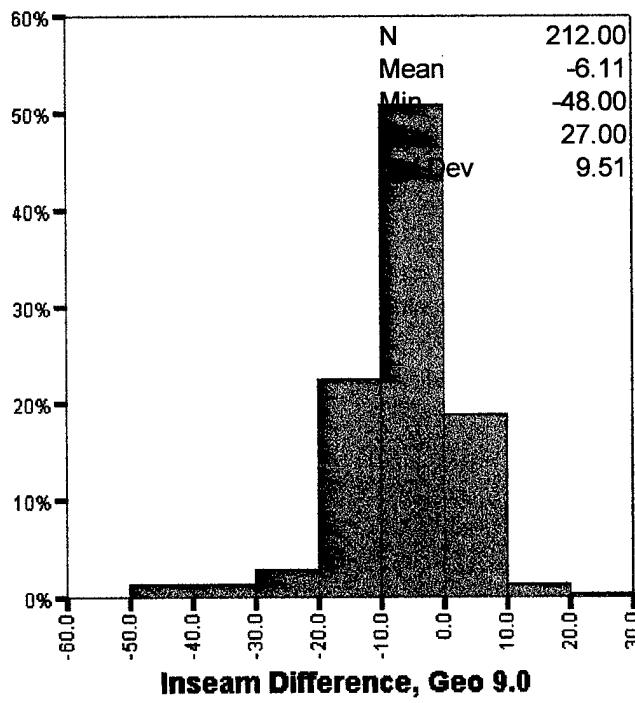
2.1.4 ARNscan 9.0 Statistics Tool Evaluation

ARNscan 9.0 also introduced a Statistical Tool for analysis of the scan measurements. The BRC assessment of the statistics tool consisted of evaluating the "human factors" aspects of the window text and layout and validating the statistical output.

The first impression was that the window is just a bit busy and difficult to understand. We suggest that the window could be broken down into two where the summary statistics and frequencies would be included in the main window and viewing the raw subject data would optional. The reason behind this suggestion is that it is not necessary to look at the individual cases unless the statistics indicate the need to do so, such as in the instance of an extreme minimum or maximum.

Without looking at the documentation, we were initially unclear about the meaning of "high", "low", "shift factor", and "bucket." After looking at the documentation and working with the different options, it began to make sense; however, it could be more user-friendly. We suggest either more descriptive terminology or some sort of Help feature.

We found the "shift factor" utility to be very handy as a measurement evaluation tool. Often, ARNScan measurements are simply offset from Expert measurements by some nearly constant amount. The ability to interactively translate the data by a constant and compute the statistics based on the translated data is a great improvement. It makes it much easier and faster to determine whether altering the measurement algorithm by that constant would result in greater overall accuracy.

In validating the statistics, we found only one problem. What is labeled the average difference is not the average difference; it is the mean <u>absolute</u> difference (MAD). (By the way, we prefer the use of the term "mean" to the term "average".) The use of absolute differences in calculating the mean is inconsistent with the calculations for the other statistics. The standard deviation, minimum, maximum, and frequencies are found using the signed differences. To fix the problem, we should at least be consistent. We must decide what we are interested in knowing. In our opinion, we are more interested in the signed differences, especially with respect to the frequencies. We can always figure the frequency of absolute differences by examining the frequency of signed differences. If absolute differences are deemed most meaningful, they should be properly labeled and used consistently for all statistics. Another possible solution might be to include both sets of statistics either automatically or by allowing the user to decide which she prefers.

Overall, we find the statistics tool to be a worthwhile feature. It provides a lot of useful and accurate information and is relatively easy to understand once you have read the documentation and worked with it a bit.

2.2 Testing and Evaluation

2.2.1 Natick ARNscan Software Validation Task

2.2.1.1 Introduction
During the first year of T2P5, approximately 35 subjects were recorded for use as test data using the Cyberware WB4 Whole Body Scanner at the U. S. Army Natick (MA) Research, Development, and Engineering Center. These subjects were Army personnel at Natick, along with several civilians. The subjects were scanned in a variety of positions, and had traditional anthropometric measurements taken by Natick anthropologists. While useful for testing developing ARNscan software, it was realized that a larger, statistically significant sample would be needed because of the variability in human size/shape. In addition, the pending field test of hardware and software at MCRD-San Diego needed preparation in the form of a test of scanning posture, software, and hardware. In order to properly test software, the new data would have to be recorded under controlled conditions with traditional measurements and surface landmarks also recorded that were relevant to size selection.

The active T2P5 Partners (Anthrotech, Cyberware, Ohio U., and BRC) all participated fully in planning this task. Natick anthropologists Dr. Brian Corner and Mr. Stephen Paquette were also key in facilitating our use of the WB4 scanner in their laboratory. Arthur D. Little, Inc., was hired to recruit civilian subjects from the area, and deliver them to the scanning room at Natick on a fixed schedule.

2.2.1.2 Scanning and Measurement
One hundred twenty two subjects were scanned and measured at three sessions in October, November, and December 1997. After the second session, scan data were measured using CyScan.r6 (ARNscan version 6). The scan measurements taken were neck, chest, waist, and overarm circumferences, inseam and sleeve lengths, and shoulder breadth. For several measurements (chest, waist, and sleeve length) two different measurement functions were used to test different algorithms.

While there were several weeks after the first (October) scan session to at least partly analyze the data, it wasn't possible to analyze the November scan data thoroughly before the December scanning. With the good initial results, it was felt that measurement functions needed to be changed at the time. However, after the final scanning and measuring was mostly completed by the end of this month, it was apparent that there were many more subject measurements with significant differences from the tape values. BRC began to try to organize the results so that the problems could be investigated. The subjects were first separated by sex, then categorized visually by body type estimate (a=thin, b=medium, c=fat, d=body builder). Tables computing differences in tape and scan measurement values were then created.

As the final scan measurements were being made, it was apparent that one of the chest measurement functions was yielding poor results. In this function, the location for where the chest measurement is taken is found by first starting at the landmark at the underarm

(scye), then iteratively working down the chest to find the point where the chest is most prominent. Unfortunately, it was found that 'pot bellies' were being identified by the function wrongly as the location for measurement. The function was then modified and has been 100% successful in locating the correct point for the chest measurement. The subjects were remeasured with this function.

The use of one landmark as a starting point in finding precise measurement locations is an example of how best to automate many of the measurements. Most measurements are taken at precise points. However, many of the points and the measurements there are maxima or mimima of some kind. These extremes can be found iteratively by first finding a start point, then working through the whole region where the maximum/minimum should be found. The value of this for automation is that the starting point does not have to be precisely found - only an approximation is needed in the cases where we are using this strategy. Thus, it is much simpler to automatically find a usable start point.

Anthrotech in Final technical Report AR06 reported the analysis of all measurement data.

The scans recorded for this project were analyzed using a version of ARNscan now superseded by more advanced versions which are more automated, consistent, and accurate. However, the scans represent a unique collection of adult male and female civilians which are a valuable resource for future research and development projects. The data are archived at the sites of the ARN Partners as well as at Natick (POC Stephen Paquette).

2.2.2 San Diego Marine Corp Recruit Depot Field Test.

Up to the time of the MCRD Field test in 1998, the Cyberware scanner and ARNscan software had only been used in controlled laboratory conditions. While the goal of the project was to develop software for uniform sizing, no specific application site had been identified. With the announcement of the Virtual Prime Vendor (VPV) project at the MCRD San Diego in 1997, the T2P5 group proposed a field test for the 3D body scanner and ARNscan software. This would give T2P5 a site to test the hardware and software under field conditions, and to work with the VPV in integrating uniform issuing with the wider logistics of a base.

BRC led the initial planning effort and functioned as liaison with the staff at MCRD. Our strategy in planning was to learn as much as possible about the apparel issuing operation and the schedules of the recruits in order to maximize the amount and value of testing while minimizing the impact on the normal operations of the base. A plan was developed to scan and measure recruits in parallel with the three clothing issuing points:

(1) On arrival during the first night the recruits are on base (Training Day 0, or T0). At this point they are issued minimal apparel, principally sweats, battle dress uniforms (BDU's), and athletic shoes. The two objectives for T2P5 to scan at this point were to test BDU size selection tables developed by SPSU, and to record the recruits before physical training. The latter objective would help in any efforts to predict body size/shape changes during training.

(2) At first fit of the dress uniform (T19). Four weeks into their training, the recruits are fit for dress uniforms. Our objectives for scanning at this point were to (a) test the hardware and software in the clothing building conditions, (b) test the logistics of moving recruits through the scanner under time constraints, (c) record the same recruits scanned at T0 to measure changes in body size, (d) acquire a database useful for further development and testing of size selection tables by SPSU, and (e) record all size and alteration information possible concerning the uniform issued to the scanned recruits.

(3) At final fit of dress uniforms during graduation week (T60). After first fit, the recruits go to Camp Pendleton for boot camp and field training. Information from the MCRD staff and tailors was that there were often significant size changes in the recruits during this period. Our objective was to record those changes for predictive models, and to increase the database for size selection development.

After completion of the Natick Validation Tests and further software development based on those results, BRC consulted with MCRD concerning dates for the three test scanning sessions. We wished to conduct the Field Test during a period when there were the fewest recruits at MCRD to minimize the problems of dealing with large numbers and the time constraints that would put on both T2P5 and the MCRD staff. Because we wished to follow the same recruits through their thirteen weeks of training, we needed to start early in the year so that we would avoid the large summer recruit classes. It was decided to follow two recruit classes at T0 during the weeks of March 16th and 23rd, 1998. First fit (T19) scanning would be April 14-15 and April 21-22, and final fit scanning (T60) June 8th and 15th. These schedules were followed.

The protocol at each scanning session called for the recruits to be measured using standard anthropometric techniques, as well as being recorded by the Cyberware WB4 scanner. Anthropometry was taken by Anthrotech and Natick personnel. Each recruit was scanned once in a "standard" position: feet 30cm apart, palms facing toward the body, 30cm from the body.

Recruits scanned at each period were:
T0 – 340
T19 – 202
T60 – 188

Numbers decreased for two reasons. First, some recruits dropped out or fell back in their training schedule. Second, at T19, one platoon containing recruits we were following from T0 were fit with uniforms a week earlier than our scheduled called for. Thus, we were unable to scan them at first fit.

The results for measurements from scans and anthropometry are analyzed in the Anthrotech report for this project as well as here. In order not to duplicate the Anthrotech effort, this report concentrates on the relevance of the scanning results to software development. Thus, the section on Software Development uses the MCRD scan measurements as a test bed for evaluating software functions. BRC holds a database of all anthropometry and scan measurements in the file ARNscanMCRDmeasurements.xls.

2.3 Size Selection Support

Ms. Carol Ring, Apparel & Textile Dept., Southern Polytechnic State University, Marietta, Georgia (an ARN Partner) was hired as a consultant from November 1997 through May 1998 to develop size selection tables to convert ARNscan body scan measurements into dress uniform sizes for Marine Corp recruits. The details of her activities will be found now in the Interim Progress Reports for this delivery order (BR0301/0598.ipr), and for SPSU (ST03**.ipr). Below is a summary of activities funded under a consulting agreement to BRC, as well as a description of the BRC support for her work through the end of this D. O.

Ring first visited the USMC uniform designers in Albany, GA, to discuss the project and access the patterns and fit rules for dress uniform pieces (green and blue trousers, long-sleeved shirt, and dress coat). Electronic versions of the patterns were used to compute and verify design specifications for sizes and alterations. By February 1998, first versions of stock size selection rules were produced. BRC then converted the size selection rules into c-code for automation in ARNscan.

Ring traveled to San Diego for the scanning of Marine recruits during their first fit (T19) of dress uniforms April 19-20, 1998. Ring worked with the MCRD tailor contractors to understand the fit and alteration process. This included measuring altered uniforms for differences from stock size specifications. Her information was combined with other information concerning sizes issued, alterations, second fit changes, and ARNscan measurements for the recruits. All of this data was used by Ring to modify and test new size selection tables. Ring used ARNscan measurements from 70 recruits, while BRC used measurements from the remaining 139 recruits from the T19 scanning session to produce size selections which could be compared with actual sizes issued at MCRD for these same recruits. Ring analyzed these results and continued to revise the tables and comment on the quality of measurements used for input. BRC responded by graphically analyzing problem subjects to better understand the sources for mis-fits. These results were transmitted to Ring for her analysis and further recommendations.

Following the expiration of the SPSU consulting agreement, BRC continued to support Ring's efforts by
1. Modifying ARNscan measurement functions to produce measurements resulting in better fits.
2. Providing revised measurement results for re-testing of size selection tables.
3. Assisting in applying size selection tables to recruit measurements, then transmitting the results to Ring for her analysis.

3.0 Summary

3.1 Results Summarized.

BRC had a unique place in Project T2P5 because of our previous experience and expertise in anthropometry, computer software development, statistical analysis, 3D human body modeling, and scientific testing. The role of BRC in Project T2P5 was twofold: administrative and technical. In the first role, Robert Beecher was the initial project coordinator among the ARN Partners involved, working to develop and administer coordination plans which decided upon the apparel measurement information needed from 3D body scans, lead the Natick Validation Study to build a database for software testing, and lead the initial planning for the MCRD San Diego Field Test. This database contains over 1400 scan files.

In the technical role, BRC developed algorithms and source code for several measurement functions in the ARNscan computer program extracting measurements from 3D body scans, and was the principal in testing and evaluating the software and in recommending improvements. BRC also supported the size selection task of SPSU by assisting in the application of size selection tables to the MCRD scans, and in advising SPSU on the technical functioning of ARNscan.

The most important results comprise the quality of the ARNscan software that measures 3D body scans and specifies Marine uniform sizes. The Table below summarizes the simple statistical results for each of the measurements evaluated. Please note that these statistics do not in themselves demonstrate the quality of the software. See the text discussion.

Table: Summary Statistics For ARNscan Software Measurement Functions

Mean D: Mean Difference ARNscan minus Expert measurements
Std Dev: Standard Deviation
Units = millimeters   1 inch = 25.4mm

Measurement	ARNscan ver. 7.3		ARNscan ver. 8.0		ARNscan ver. 9.0	
	Mean D	Std Dev	Mean D	Std Dev	Mean D	Std Dev
Stature (Height)	-23.7	22.4	-23.8	13.8	-29.1	12.0
Neck Circ.	-2.4	7.5	3.0	6.4	1.4	6.7
Chest Circ.	2.2*	70.8*	27.6	24.8	25.0	26.2
Waist Circ.	4.2	26.5	13.6	17.4	10.6	16.3
Seat Circ.	25.6	16.0	4.7	8.6	32.0	17.0
Cross Shoulder	15.2	18.2	14.7	14.8	16.1	18.2
Sleeve Length	-64.8	20.5	-60.4	37.9	-1.5	16.2
Pant Inseam	6.6	9.2	-9.7	14.0	-6.1	9.5

*Several versions were tested. See section 2.1.3.3 for a full discussion.

While the mean values are important, the standard deviation may be more important because they measure the consistency of the ARNscan measurement with respect to the

Expert. The smaller the standard deviation, the more consistent are the difference between ARNscan and Expert. That is, if for Chest Circumference all ARNscan measurements were 20mm larger than the Expert, the ARNscan software could simply shift its values by 20mm to be exactly like the Expert.

3.2 Conclusions and Recommendations.

Throughout this project, there was a tension between the goals of accuracy and automation. By the end of this delivery order, the T2P5 Partners had demonstrated in the versions of ARNscan evaluated here that full automation (no subject marking and no operator interaction) with consistent accuracy was attainable using the available software tools for all measurements except Sleeve Length. Consistent results for Sleeve Length await a software tool that can accurately locate the sleeve end point.

A next step for improving the consistency of measurements should be the development of error-checking software tools. A Repeatability Test performed after the conclusion of this delivery order also suggests areas for improvement, including changes in subject posing. A review by software developers of all of the available software tools developed by the T2P5 Partners should be carried out in order to re-evaluate quality of successive versions of ARNscan.

4.0 Appendix

Waist Height Prediction

Functions to compute Waist Ht Man, Chest Ht Geo, and Seat Ht Geo were developed and incorporated into CyScan. Data for these measurements were gathered for the San Diego recruits at T-0. These data were then used to compute a regression equation to estimate Waist Ht from Chest Ht Geo, Seat Ht Geo, and Stature Geo. The regression equation is as follows:

$$\text{Waist Ht} = (.094 * \text{Stature}) + (.383 * \text{Chest Ht}) + (.474 * \text{Seat Ht}) + 45.751$$

This equation is associated with an R of .94 indicating a very strong linear relationship between the measured and predicted values for Waist Ht. The following table contains summary statistics for the measured Waist Ht Man 1 and the predicted value for waist height. Upon comparison, the means and standard deviations are quite similar. However, the range for predicted values does not extend as low as that for the measured values.

Descriptive Statistics

	N	Minimum	Maximum	Mean	Std. Deviation
Waist Ht Man 1	283	924.00	1206.00	1066.7915	49.7060
Predicted Value	274	962.64	1203.52	1065.0483	45.8991
Valid N (listwise)	273				

Bivariate plots of each independent variable with measured and predicted waist height indicate that there is one subject who appears to have a low waist height with respect to the other subjects. Cobb1112 has a measured waist height of 924 mm with the next highest being 956 mm. This could be an aberrant data value, or the subject could be unusual, or we just didn't sample anyone with values in between. I don't believe this subject has much influence on the regression equation, because the trend in the rest of the data is very strong. Predictions shouldn't be a problem unless this subject is not all that unusual and we don't have a complete waist height distribution in our sample.

A complete listing of the SPSS output is attached.

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Seat Ht Geo 1

Chest Ht Geo 1

Stature Geo 1

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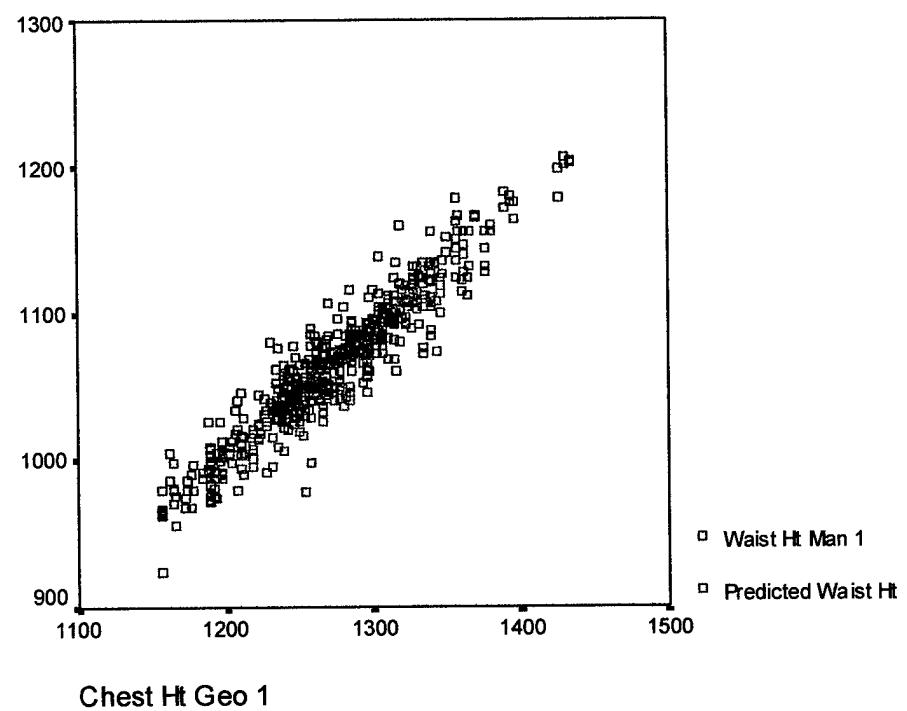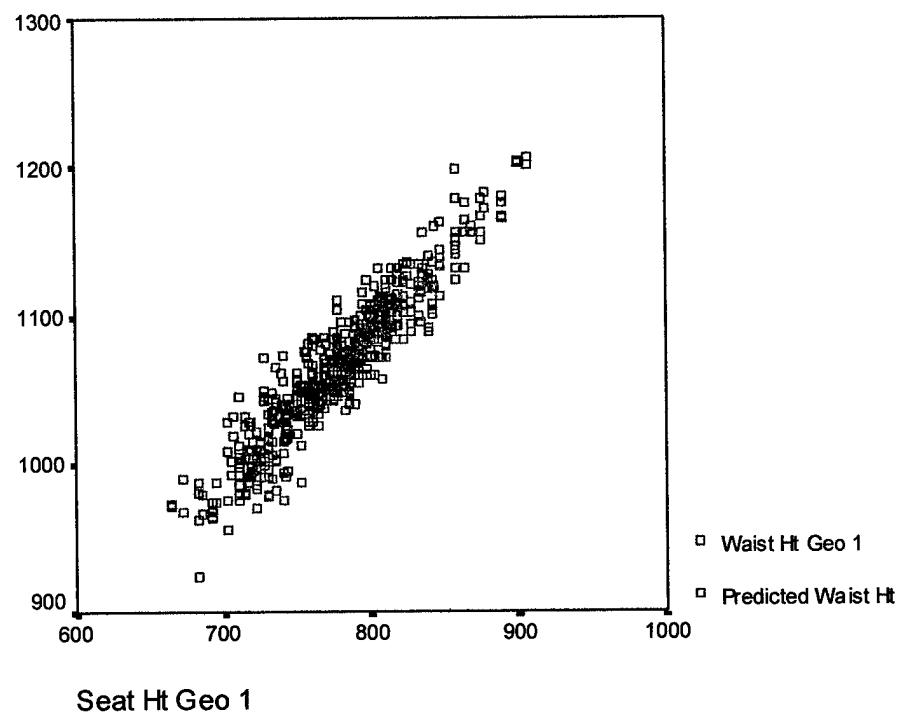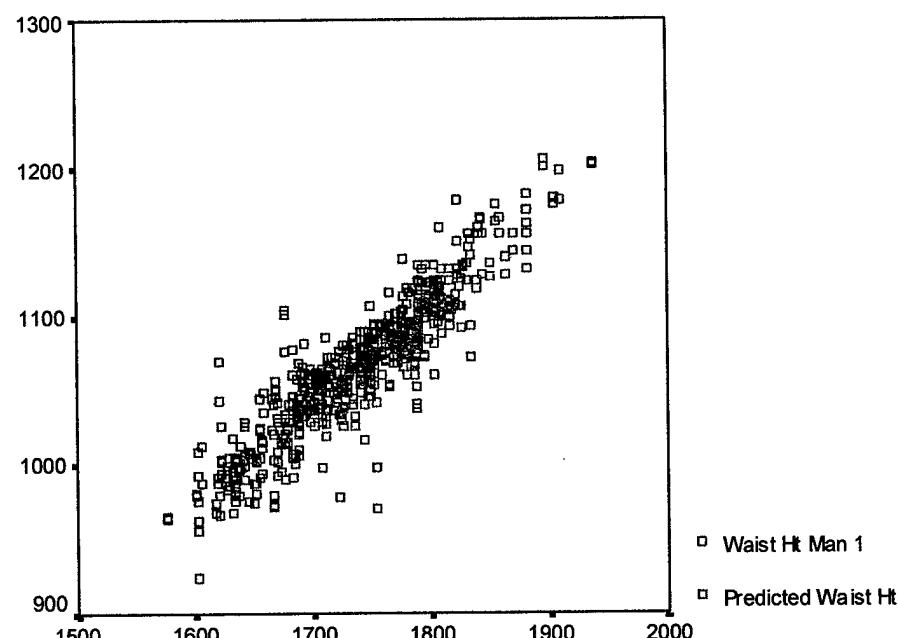
Attachment: SPSS Output Listing

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.939	.882	.880	16.9434

a Predictors: (Constant), Chest Ht Geo 1, Seat Ht Geo 1, Stature Geo 1
b Dependent Variable: Waist Ht Manual 1

ANOVA

	Sum of Squares	df	Mean Square	F	Sig.
Regression	574467.537	3	191489.179	667.029	.000
Residual	77223.892	269	287.078		
Total	651691.429	272			

a Predictors: (Constant), Chest Ht Geo 1, Seat Ht Geo 1, Stature Geo 1
b Dependent Variable: Waist Ht Manual 1

Coefficients

	Unstandardized Coefficients		Standardized Coefficients	t	Sig.	95% CI for B	
	B	Std. Error	Beta			Lower Bound	Upper Bound
(Constant)	45.751	28.485		1.606	.109	-10.330	101.833
Stature Geo 1	9.376E-02	.044	.127	2.149	.033	.008	.180
Seat Ht Geo 1	.474	.051	.427	9.325	.000	.374	.574
Chest Ht Geo 1	.383	.062	.418	6.182	.000	.261	.505

a Dependent Variable: Waist Ht Manual 1

Casewise Diagnostics

Case Number	Std. Residual	Waist Ht Manual 1	Predicted Value	Residual
208	-3.289	978.00	1033.7272	-55.7272

a Dependent Variable: Waist Ht Manual 1

Residuals Statistics

	Minimum	Maximum	Mean	Std. Deviation	N
Predicted Value	962.6447	1203.5164	1065.1429	45.9566	273
Std. Predicted Value	-2.230	3.011	.000	1.000	273
Standard Error of Predicted Value	1.0376	6.7035	1.9283	.6998	273
Adjusted Predicted Value	963.5217	1203.5768	1065.1513	45.9235	273
Residual	-55.7272	41.8904	5.414E-14	16.8497	273
Std. Residual	-3.289	2.472	.000	.994	273
Stud. Residual	-3.314	2.492	.000	1.003	273
Deleted Residual	-56.5622	42.5513	-8.4273E-03	17.1285	273
Stud. Deleted Residual	-3.377	2.516	.000	1.006	273
Mahal. Distance	.024	41.580	2.989	3.792	273
Cook's Distance	.000	.155	.004	.011	273
Centered Leverage Value	.000	.153	.011	.014	273

a Dependent Variable: Waist Ht Manual 1